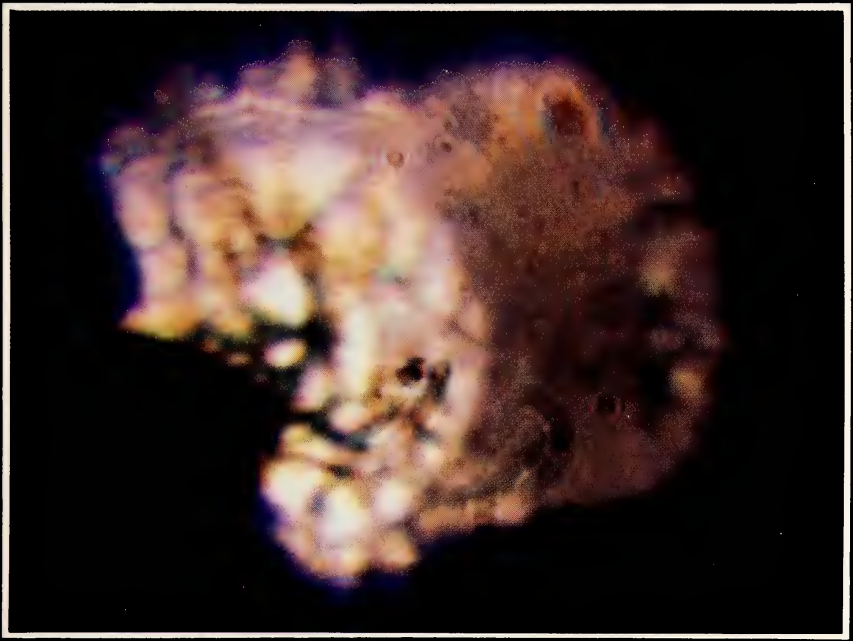
CARNEGIE INSTITUTION
OF WASHINGTON

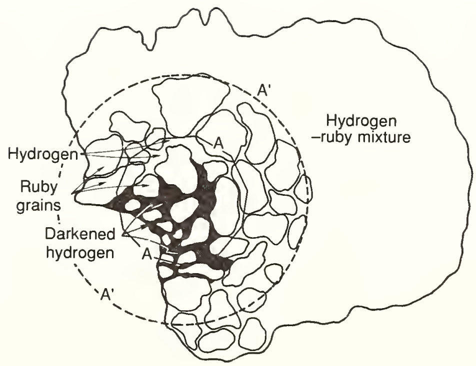


Metallization transition in hydrogen

# Year Book 88

## 1988–1989

*The Observatories*
*Geophysical Laboratory*
*Department of Embryology*
*Department of Plant Biology*
*Department of Terrestrial Magnetism*




*Cover:* Photomicrograph of solid hydrogen and $Al_2O_3$ ruby sample within the high-pressure diamond-anvil cell, obtained during a recent experimental run by Ho-kwang Mao and Russell Hemley at the Geophysical Laboratory. The hydrogen veins toward the center *A* (see map, above) appear darkened and are nearly opaque at the pressure 250–300 GPa. The opacity at that high pressure is tell-tale evidence of predicted metallization transition. See pp. 138–139. (From *Science 244*, 23 June 1989, pp. 1462–1465, copyright 1989 by the American Association for the Advancement of Science.)

# *Carnegie Institution*

*OF WASHINGTON*

# *Year Book 88*

***The President's Report***

***July 1988–June 1989***

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# *Contents*

# *President and Trustees*



[1]From May 5, 1989
[2]To March 2, 1989

# *Former Presidents and Trustees*



Under the original charter, from the date of organization until April 28, 1904, the following were *ex officio* members of the Board of Trustees: the President of the United States, the President of the Senate, the Speaker of the House of Representatives, the Secretary of the Smithsonian Institution, and the President of the National Academy of Sciences.

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| Marshall Hornblower | *Counsel* |

[1]Name changed from Mount Wilson and Las Campanas Observatories in February 1989
[2]Appointed Director, September 29, 1989
[3]Resigned as Director, October 28, 1988

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# *President's Commentary*

Barbara McClintock, in Root Hall during Carnegie Evening, May 4, 1989. The occasion honored McClintock and her extraordinary discovery, decades earlier at Carnegie's Department of Genetics, of transposable genetic elements in maize.

From the scientists, social and natural, we derive our belief in the unifying force of the search for knowledge, and in the harmonies among forms of knowledge, even as knowledge, increasing, tends to fragment itself and us with it. From them we learn what we should never forget, that to view nature justly, nature human and material, we must eschew parochialism and casual labels and bureaucratic boundaries and seek to see the truth from as many vantage points as humankind can summon.

—*A. Bartlett Giamatti**

A rich variety of scientific and institutional events marked my first full year as president. Threading through all, giving cohesion to the variety, was a growing appreciation for the Institution's remarkable independence, both intellectual and financial. Such independence is becoming increasingly rare in American research institutions, although it was once their hallmark. Thus, the freedom of our investigators not only gives us unique opportunities in science, but it is a reminder to others of the value and privilege of standing on one's own.

Our independence is of course not absolute. The increasing complexity of the modern world demands that we cooperate with the needs, customs, rules, and regulations determined by society to serve the common good. And the increasing complexity and costs of modern scientific research require that we seek to augment our considerable institutional funds with support from private individuals and foundations and the federal government. In doing so, however, we remain cautious and attentive to preserving the Institution's fundamental aim: to permit individual scientists the freedom to follow their own ideas.

The annual Carnegie Evening in May of 1989 underscored the

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*From *A Free and Ordered Space, The Real World of the University*, by A. Bartlett Giamatti, by permission of W.W. Norton & Company, Inc., Copyright ©1988 by A. Bartlett Giamatti (p. 160).

interplay of our history and current scientific research, and the strengths the Institution derives from that tradition. The Evening honored Carnegie's Distinguished Service Member, Barbara McClintock. Nina Fedoroff of the Department of Embryology was the speaker. Fedoroff described with verve and clarity her studies, at the level of DNA molecules, of the moveable genetic elements in the chromosomes of maize. These are the same entities that McClintock discovered forty years ago using classical genetic and cytogenetic techniques. (Readers of *Year Book 87* will recall Fedoroff's essay summarizing some of her experimental work.)

At the end of the lecture, McClintock rose and spoke informally before the filled Root Auditorium. She paid tribute to the Institution's dedication to scientific freedom, and she lauded earlier Carnegie administrations for supporting her during years when most biologists failed to comprehend the significance of her work. We, as an institution, will continue to honor her extraordinary example through the Barbara McClintock Fellowship Fund, which will support postdoctoral fellows in Carnegie laboratories.

Altogether, it was a gala and inspiring Evening—an unforgettable occasion bringing together Carnegie people of several generations and our guests in a spirited celebration of science.

### *Science as Frontier*

Remaining independent, standing on one's own, are qualities conveyed in the frequent metaphoric expression, science as "frontier." In 1944, when science was so described in a correspondence between President Franklin D. Roosevelt and Carnegie's president, Vannevar Bush, the metaphor signified a fresh and inspiring vision for the future. In November of that year, Roosevelt wrote to Bush:

> New frontiers of the mind are before us, and if they are pioneered with the same vision, boldness, and drive with which we have waged this war, we can create a fuller and more fruitful employment and a fuller and more fruitful life.*

Roosevelt went on to ask Bush how the lessons learned from coordination of the nation's scientific effort during World War II

*Vannevar Bush, *Science, The Endless Frontier. Report to the President on a Program for Postwar Scientific Research*, U.S. Government Printing Office, 1945.

could be employed in peacetime. Bush's report in July 1945, *Science, The Endless Frontier*, established the framework for American science that has succeeded for almost half a century. Bush's vision led to the establishment of the National Science Foundation in 1950. Together with the contemporaneous expansion of the National Institutes of Health, the founding and steady growth of the National Science Foundation demonstrated society's commitment to foster fundamental research in the national interest.

The optimism inherent in the word frontier as used by Bush and Roosevelt is now attentuated, partly from incessant use and partly because of widespread disquiet about the eventual consequences of new scientific findings. Moreover, the word frontier in American history has itself acquired new nuance. Whereas to its early historians, the American West was a romantic nostalgia, by 1945 such myths were already fading under rigorous examination. A deeper, more complex understanding of the historical frontier has emerged—to include greater attention to the people and territory that existed before the pioneers, and to the diverse ethnic populations that contributed to the geographical expansion.

We scientists welcome the new, less-biased insights, and we recognize a parallel circumstance facing ourselves. Scientists, by reevaluating our own myths, will also enhance the public understanding of our work. We, and the society in which we live, will benefit if science's image as some sort of modern "holy grail" of infallible truth is dispelled.

The frontier of the American West, moving in both space and time, had, after all, both a before and an after. Expansion brought problems as well as progress. So too in science. New ideas, new methods, new instruments replace the old, at dizzying rates. The concepts and the culture of science change apace, often with inadequate contemplation of what is being lost.

We have been reminded of these considerations by the extensive attention paid recently by the Congress and the press to the integrity of the scientific enterprise. Matters of public attention have included alleged and proven instances of dishonesty in research, problems following intensified efforts to convert new research findings into economically productive enterprises, and the criteria for academic advancement, particularly the perceived necessity to "publish or perish." Public judgments by poorly informed individuals, and less-than-accurate accounts, hardly allow for serious contemplation of the real and challenging issues behind the headlines. These matters are of

marginal direct concern to Carnegie scientists, but they are of profound interest to us because they involve our scholarly community and the culture in which we work. We at Carnegie are by and large privileged in our ability to stand relatively free from the pressures cited here—an inheritance from Andrew Carnegie and successive boards of dedicated trustees. Thus it is our responsibility to stand as a reminder of how independence and integrity undergird productive and original research.

### *New Frontiers, New Directions*

Three elements at least, and in a definite order, define the direction of expansion of a geographical frontier: the discovery of routes, the ease of following the paths, and the bounty to be found upon arrival. The same is true in scientific research, where the bounty is a better understanding of nature, not acquisition of "the truth" as the myth would have it, and where the development of new concepts, methods, and instruments constitutes the discovery of routes and the development of accessible paths.

Many of Carnegie Institution's great accomplishments, past and present, have depended on such developments. At the Geophysical Laboratory, continuing improvements have been made in the diamond-anvil high-pressure cell and in methods for detecting changes in the properties of materials contained within its transparent diamonds. Currently, the full range of temperatures and pressures found within our planet can be attained. Understanding of the Earth and its formative processes is improved by studying its components under a variety of conditions. Fundamental contributions to physics and chemistry are made. Occasionally, quite dramatic results are obtained. That happened this year, when evidence supporting the long-predicted transition of solid hydrogen to the metallic state was obtained at pressures of about 250 GPa.

The diamond-anvil cell is small, barely noticeable on a cluttered tabletop. At another extreme is the Magellan telescope with its 8-meter mirror, planned for construction in the next decade at the Carnegie Observatories' Las Campanas site. As reported in Alan Dressler's essay in this Year Book, steady progress is being made in demonstrating the technical feasibility of constructing and polishing a light-weight mirror of this large diameter. Work is also proceeding on the design of a telescope mount and housing, and photographs of a building model were

shown at the annual meeting of the Board of Trustees in May 1989.

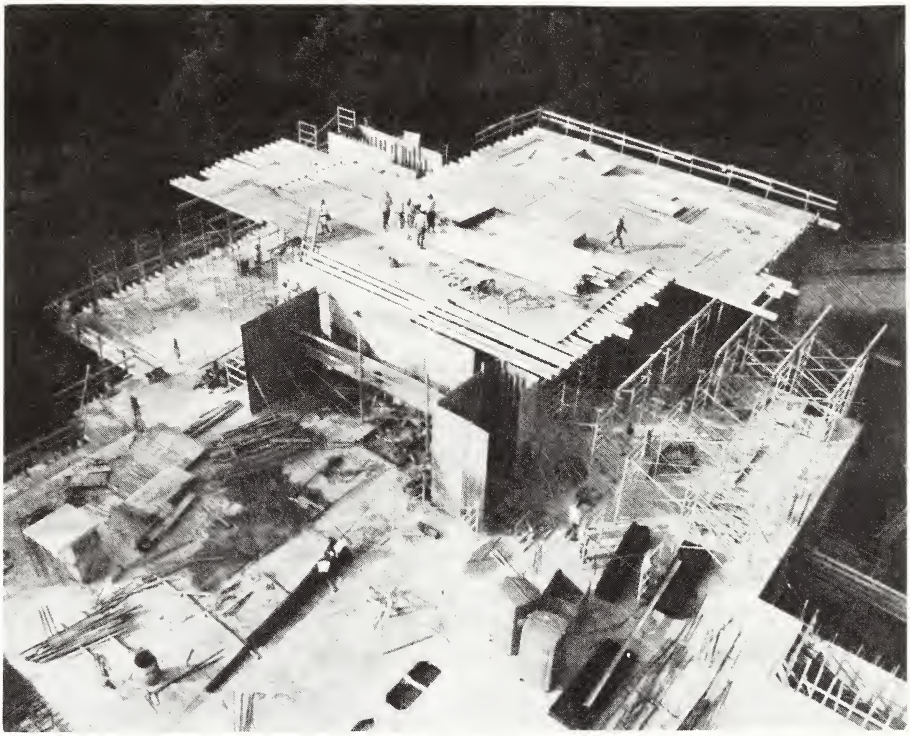
Telescope building is not a new venture for the Institution. Early Year Books report the construction of the magnificent instruments at Mount Wilson and the great discoveries made there. In early 1989, as planned, the facilities on Mount Wilson were turned over to the Mount Wilson Institute for operation, an arrangement that should become permanent in two years. Changing atmospheric conditions long ago convinced our astronomers and trustees that this would be necessary. Still, because Mount Wilson's name so long signified the Institution's preeminence in astronomy, regret accompanies the new circumstance. Our regret is, however, tempered by the spectacular observational facilities we already have in the present telescopes at Las Campanas, and by anticipation of Magellan. It is also tempered by the agreement, reached this year with the California Institute of Technology, that assures access by Carnegie astronomers to the 5-meter telescope at Palomar for at least the next five years.

In recognition of the several new arrangements, our department of astronomy is now formally named The Observatories of the Carnegie Institution of Washington, more conveniently called the Carnegie Observatories. Along with the new name, the Carnegie Observatories also have a new director—the distinguished astronomer Leonard Searle. A long-time Carnegie staff member, and acting director since August 1988, Searle was appointed director in September 1989. Searle's leadership will continue and extend the outstanding achievements of Ray Weymann and George Preston, his most immediate predecessors.

*Creativity and Intellectual Freedom*

Expansion of scientific understanding means a new perception of nature. It is important that we at Carnegie maintain an atmosphere, a "culture," that encourages original work. It is not a simple task, but experience and observation suggest a few important catalysts. One is youth. Young people bring new ideas, energy, and a healthy scepticism about established notions. That is why students at both the postdoctoral and predoctoral levels bring as much to a research group as they learn from it. It is also why we put so much stress on having adequate funds for fellows.

Another catalyst to creativity is a balance between diversity



In July 1989, the new research building at DTM's Broad Branch Road site was 20% complete. Here, workmen prepare framing for the concrete penthouse slab. The penthouse, which tops the three-story building, will house mechanical equipment.

and commonality of subdiscipline within a research area. At the Department of Embryology, for example, Carnegie staff members focus on the genetic and biochemical processes that lead to the development of multicellular living organisms from single fertilized cells. But their studies encompass a range of organisms, from plants, to insects, to vertebrates. A different kind of diversity exists in the Department of Plant Biology. Here, all staff members work on plants, but they work at different levels of biological organization, from the gene, to cells, to whole plants, to populations of plants in natural environments. Communication between scientists with different insights engendered by different daily experiences stimulates everyone toward new ways of thinking.

We expect that in time, a new balance between diversity and commonality will follow the move of the Geophysical Laboratory and the Department of Terrestrial Magnetism into new and refurbished common quarters. Ground was broken in January 1989 for the new research building at DTM's Broad Branch Road site. The different subdisciplines represented

in the two departments have a common fundamental aim: to understand the nature and history of the Earth. Speaking at the ground-breaking ceremony, Frank Press, president of the National Academy of Sciences, asked:

> What is more basic when dealing with matters of the environment than to think in terms of the origin and development of the Earth, the origin of its continents, its atmosphere, its oceans, its resources?

The diversity that invigorates research is also rooted in a group's blend of people—individuals of distinct background, temperament, and outlook beyond their particular subdiscipline. The same was true of the settlers of the western frontier. Those who made the westward expansion exciting and productive were not solely white males of Protestant, Anglo-American background, though they may seem so in popular lore. The truth is that the frontier's people represented a complex mixture of national, racial, and religious backgrounds, and both sexes contributed to the development of our continent.

Similar myths have existed in science, reinforced by the traditional placement of minorities and women in secondary positions in research groups—positions where their work, often seminal, failed to garner appropriate recognition. With respect to women, the Carnegie Institution has been more willing than many research organizations to recognize that female scientists can be as outstanding as their male colleagues. Women participate fully in our Board of Trustees, in the Administration, as staff scientists, and as postdoctoral or predoctoral fellows and associates. But we, like most American research institutions, have not yet been successful in providing full opportunities for individuals in minority groups to join the scientific enterprise.

Recognizing that the challenge of frontier work requires all the talent available, the Institution began this year to plan a science program for inner-city children. "First Light," as the Saturday science group is called, will try to engage Washington children's curiosity by raising questions about natural phenomena, and letting the children think and experiment with ways to acquire answers. Thus, we base First Light's program on one of the elements that seems critical if original scientific work is to occur: freedom of the mind.

With the children, as with staff scientists, freedom to inquire is the bulwark of scientific accomplishment. The lack of such freedom in our schools, where science teaching is didactic and often boring, is one cause of education's failure to produce

children with lifelong commitments to science. The freedom of Carnegie scientists to pursue their own lights is one reason why our departments are so productive of original research. Hatten Yoder, director emeritus of the Geophysical Laboratory, recently wrote:

> That freedom to follow whatever is critical to the solution of problems is why the Geophysical Laboratory has remained unique among research organizations. The price of such a generous measure of scientific freedom is greater personal responsibility to produce and greater accountability.*

Yoder's view of the Geophysical Laboratory is readily projected onto the whole of the Carnegie Institution.

—*Maxine F. Singer*
*October 1989*

# *Losses, Gains, and Honors*

Christopher Wright, former staff member for science policy and institutional development (1979–1983), died of cancer in Washington, D.C., on May 9, 1989, at the age of 62. Wright served at Columbia University, the Rockefeller Foundation, and the U.S. Congressional Office of Technology Assessment before coming to the Carnegie Institution. At Carnegie, he explored the interactions between science and public policy.

Robert C. Lee, former staff member at the Institution's former Department of Nutrition (1928–1944), died in Concord, New Hampshire, on September 10, 1988, at the age of 81.

Margaret McDonald Prytz, former staff member at the former Department of Genetics (1946–1968), died on December 28, 1988.

Neltje van de Velde, former research assistant at the Department of Terrestrial Magnetism (1965–1975), died on February 7, 1989. Stanley Swantkowski, retired DTM caretaker (1951–1966), died on May 15, 1989.

Francis Rowe, retired shop foreman at the Geophysical Laboratory (1938–1971), died on June 1, 1989. Robert Butler, retired building engineer at the Laboratory (1951–1968), died on April 26, 1989.

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*H. S. Yoder, Jr., "Scientific Highlights of the Geophysical Laboratory, 1905–1989," in *Annual Report of the Director, Geophysical Laboratory, 1988–1989*, p. 196.

William J. Cleary, retired animal caretaker at the Department of Embryology (1930–1975), died on December 24, 1988.

Richard Hart, retired mechanical engineer at the Department of Plant Biology (1956–1983), died on July 17, 1988.

Resigning from the Institution's Board of Trustees in May 1989 was Robert M. Pennoyer, trustee since 1968. A partner at the law firm of Patterson, Belknap, Webb & Tyler, Pennoyer served on the Institution's Finance, Nominating, and Executive Committees, and was, since 1985, chairman of the Auditing Committee. He was most recently chairman of the Visiting Committee to the Department of Terrestrial Magnetism.

Peter Bell, staff member at the Geophysical Laboratory since 1964, retired on July 1, 1989. Now vice president in charge of research at the Norton Company in Massachusetts, Bell remains affiliated with the Laboratory as adjunct senior research scientist.

Delores Sahlin, receptionist at the Observatories since 1975, retired on January 1, 1989.

Paul Schechter, staff member at the Observatories since 1982, departed in November 1988 to assume a position at the Massachusetts Institute of Technology.

*Gains*

Johnson & Johnson executive James E. Burke and former astronaut Sally K. Ride were elected to the Institution's Board of Trustees during its annual meeting in May 1989.

James E. Burke is a member of the board and chairman of the Strategic Planning Committee of Johnson & Johnson. He received his MBA degree from Harvard Business School in 1949, and joined the health care company four years later. He was named director of new products in 1955. In 1965, he was elected director and member of the executive committee, and, in 1973, he became president. From 1976 until 1989, he was chairman and chief executive officer. His outside activities include memberships on the Trilateral Commission and the National Commission on Public Service, and on the boards of IBM and the Prudential Insurance Company. He is vice chairman of the Business Council and a board member of the Council on Foreign Relations and the Business Enterprise Trust. He is also a member and formerly was chairman of the President's Commission on Executive Exchange, and is a member of the board and a former chairman of the United Negro College Fund.

Sally K. Ride was named director of the California Space

Institute of the University of California, San Diego, in September 1989. At the same time, she accepted a professorship in the University's physics department. Previously, since 1987, she had been a science fellow at Stanford University's Center for International Security and Arms Control. Ride received her Ph.D. in physics from Stanford University in 1978, and was then accepted into NASA's astronaut corps. She flew on two Space Shuttle flights and was training for a third at the time of the Challenger accident. She terminated training to serve on the Presidential Commission investigating the accident, and chaired the Commission Subcommittee on Shuttle Operations. She then took a position at NASA headquarters in Washington, D.C., as special assistant to the NASA administrator for strategic planning. In this role, she created NASA's Office of Exploration. She serves on the board of Apple Computer and is a member of the Technology Assessment Advisory Council of the U.S. Office of Technology Assessment.

Leonard Searle was appointed director of the Carnegie Observatories in October 1989. Searle, who graduated from the University of St. Andrews, Scotland, and earned the Ph.D. in astrophysics from Princeton (1956), has been a Carnegie staff member since 1968. During the past several years, he has served as associate director of the Observatories, with responsibilities for the operation of Las Campanas. He became acting director of the Carnegie Observatories in August 1988. Searle's research interests range widely over questions concerning the chemical composition of stars, star clusters, and the distribution of the chemical elements.

Andrew Z. Fire, a staff associate at the Department of Embryology since 1986, was appointed staff member on July 1, 1989. Fire studies cell differentiation in the nematode *Caenorhabditis elegans*. He received a Ph.D. from M.I.T., in 1983, then spent two years as a postdoctoral fellow at the Medical Research Council in Cambridge, England, where he developed a widely acclaimed gene transfer technique for *C. elegans*.

### *Honors*

Allan Spradling, Department of Embryology staff member and Howard Hughes Investigator, was elected to the National Academy of Sciences in April 1989. He also received the 1989 Genetics Society of America medal in July 1989.

Joseph Gall of the Department of Embryology was elected to

the American Philosophical Society in April 1989. In September 1989 he received the V.D. Mattia Award from Hoffman-La Roche Inc. for outstanding contributions to biomedical research.

Ho-kwang Mao received the 1989 P. W. Bridgman Gold Medal, awarded by the International Association for the Advancement of High Pressure Science and Technology, in July 1989. The Medal is the premier international recognition of contributions in research at high pressure.

Olle Björkman of the Department of Plant Biology was elected to the Royal Swedish Academy of Sciences in November 1989.

Nina Fedoroff of the Department of Embryology was elected to the American Academy of Arts and Sciences in May 1989.

Steven McKnight, like Spradling a Hughes Investigator at the Department of Embryology, received the 1989 Eli Lilly Award from the Eli Lilly Co. on May 14, 1989. McKnight, William Landschulz, and Peter Johnson, all of Embryology, received the 1989 Newcomb-Cleveland Prize from *Science* for their papers on the leucine zipper.

Department of Embryology research associate Ronan O'Rahilly received a Doctor of Science (Honoris Causa) degree from the University College, Cork, Ireland, on May 8, 1989.

Winslow Briggs, director of the Department of Plant Biology, was Cecil and Ida Green Visiting Professor at the University of British Columbia during October 1988.

Vera Rubin, DTM staff member, was the Beatrice Tinsley Visiting Professor at the Department of Astronomy, University of Texas, Austin, for most of the fall 1988 term.

Donald Brown, director of the Department of Embryology, was Walker-Ames Visiting Professor of Zoology, Biochemistry, and Pharmacology at the University of Washington, Seattle, during May 1989.

Geophysical Laboratory staff member Robert Hazen was guest of honor at the University of Cincinnati Physics Department annual graduate students' guest speaker colloquium, April 21, 1989. In January 1989, Hazen and his wife, Margaret, authors of *The Music Men*, received the 1989 ASCAP Deems Taylor Award for outstanding writing on American music.

William Landschulz, a predoctoral fellow at Embryology, received the 1989 Michael A. Shanoff Award from Johns Hopkins University.

Observatories postdoctoral fellow Suzanne Hawley received an outstanding dissertation award from the University of Texas, Austin.

Former DTM postdoctoral fellow Paul Rydelek (1986–1988) was awarded a Humboldt Foundation Fellowship for study at Schiltach Observatory near Karlsruhe, Germany.

Former DTM postdoctoral fellow Mizuho Ishida (1982–1983) received the Saruhashi Prize in May 1989. This prize is awarded annually to an outstanding Japanese woman scientist.

Carnegie trustee and former president James D. Ebert was reelected to his third four-year term as vice president of the National Academy of Sciences.

Sandra Faber was elected a member of the American Academy of Arts and Sciences in May 1989.

Richard E. Heckert, chairman of the Board, received Citizen of the Year Award on November 1, 1988, from the Penjerdel Council, a tri-state association of business, industry, and the professions serving the Delaware Valley. On October 29, 1988, he received an honorary Doctorate of Science from the University of Delaware.

Antonia Ax:son Johnson received the degree of Doctor of Laws (Honoris Causa) at Bishop's University, Lennoxville, Quebec, on May 27, 1989.

J. Irwin Miller was among the first four inductees into the Central Indiana Business Hall of Fame.

Paul F. Oreffice was given an honorary Doctor of Laws degree at Clemson University on August 6, 1988.

Howard A. Schneiderman received the Marine Biological Laboratory's Distinguished Leadership Award on August 5, 1988.

Charles Townes received a Doctor of Humane Letters from the University of South Florida on April 29, 1989.

Maxine Singer, president of the Carnegie Institution, was the National Science Foundation Graduate Fellowships Commemorative Lecturer on May 17 at the American Society of Microbiology's annual meeting.

# *Department of Embryology*

Staff of the Department of Embryology. First row sitting (left to right): K.C. Chow, Don Brown, Charles Emerson, Amity Arora, Lynn Yue, Lena Lee, Yun-bo Shi, Chuck Vinson, Joe Gall, Mitzi Baker, Eve Walton, Celeste Berg. Second row sitting: Bob Kingsbury, Mei Hsu, Julia Kay, Anne Rosenwald, Pat Englar, Sue Satchell, Ellen Cammon, Donna Somerville, Pat Cammon, Dianne Thompson, Eileen Hogan. Third row: Keith Joho, Jim Montoya, Tony Futerman, Nina Fedoroff, Ken Vernick, Denise Montell, Sandy Lazarowitz, Alan Friedman, Tony Winiski, David Schwartz, Pat DiMario, Brenda Peculis, Dianne Stern, Earl Potts, Yoshio Yaoita. Fourth row: Christine Norman, Se-jin Lee, Jeff Kingsbury, Caroline Crilley, George Rutherford, Jody Banks, Bob Palmer, Kelly LaMarco, Dick Pagano, Margarete Heck, Mike Koval, Tony Ting, Gary Karpen, Brian Eliceiri, Allan Spradling, Joe Vokroy, Patrick Masson, Peter Hoffmann-Bleihauer, Michael Jantsch, Zheng-an Wu, Tony Brooks.

## *The Director's Essay*

Developmental biology is not a discipline, it is a set of questions. These questions have been asked for centuries, not only by biologists but by every curious person who has watched an embryo develop or wondered about the remarkable complexity and organization of plants and animals.

What is new is the way that scientists now study development. For the first half of this century, there was little cross-fertilization of embryology with other fields of biology. That insularity has changed. Those of us who call ourselves developmental biologists are deeply involved in all areas of molecular biology; we depend upon using and contribute ever-changing methods to a vast pool of rapidly advancing knowledge. The successful scientist focuses on an important problem in great depth, withstanding the fashions of research while remaining up to date with and, most importantly, unintimidated by the rapid change in methods. To be seduced by fashion means derivative research; to be unresponsive to change leads to obsolescence. The success of our science is the result of this balancing act.

### *Analysis of Large DNA Molecules*

David Schwartz examines very large DNA molecules with the goal of developing new methods to help in understanding the total genetic complement of DNA, especially of humans. A typical human chromosome contains a continuous, huge piece of DNA more than an inch long; the total length of DNA in a single human cell when all pieces are laid end-to-end is approximately six feet.

The largest piece of DNA that can be studied by conventional methods without its breaking is about 10–20 microns long. In the early 1980's, Schwartz invented a new method, termed pulsed electrophoresis, that can characterize DNA molecules up to 500 microns long. Pulsed electrophoresis separates large DNA molecules by size by means of a pulsed electrical field, which forces the molecules through a tight gel matrix (very much like gelatin). The DNA molecules are thought to move snakelike through the gel matrix.

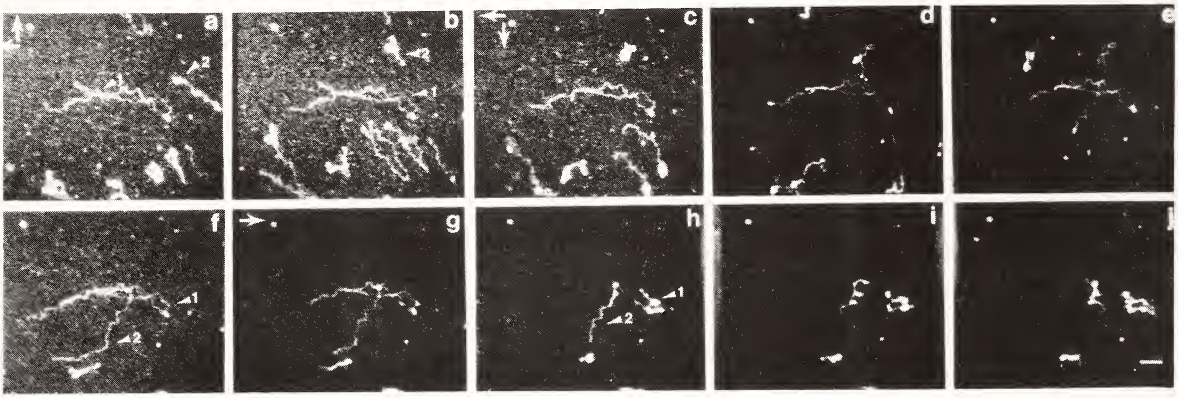

Fig. 1. A time-lapse photographic series of molecular motions obtained roughly 30 seconds apart. The threadlike objects are individual DNA molecules moving through the gel matrix. The arrows in the upper left corner of each frame show the direction of the two perpendicularly oriented applied electrical fields which were pulsed alternately on and off at 3-second intervals. The bar in frame *j* shows the scale (10 microns).

Schwartz and Michael Koval used microscopy to visualize discrete, fluorescently labeled DNA molecules as they move through agarose (Fig. 1). Collectively, their time-lapse images provide insight into the choreography of large DNA molecules as they move through a confining matrix during pulsed electrophoresis. These experiments provided a basis for new methods for analyzing single DNA molecules.

### *Chromosome Segregation at Mitosis*

When a eukaryotic cell divides, each daughter cell receives an identical complement of DNA by the precise replication and segregation of the parent cell's chromosomes. After the chromosomes replicate, the sister strands (chromatids) for a time remain associated: a specialized region of each chromosome (the kinetochore) attaches to long filaments called microtubules that emanate from the poles of a newly formed mitotic spindle. Chromosome segregation then involves two discrete steps: (1) sister strands separate from each other and move to the poles of the spindle, and (2) the poles move apart toward opposite sides of the cell. The molecular mechanism of this process, studied by Douglas Koshland and colleagues, remains obscure.

Koshland's laboratory has been studying chromosome segregation in the yeast *Saccharomyces cerevisiae*. Many basic cellular processes appear to be highly conserved among all eukaryotes, and this simple unicellular organism is particularly suited for analysis of this complex function with genetic tools. Genetic assays have been

developed by Koshland and others to determine whether dividing cells receive the proper number of chromosomes, thus identifying mutants that are defective in chromosome segregation. Are these mutants defective in kinetochore function, in microtubule assembly, or in other aspects of chromosome movement? To address these questions, Koshland and colleagues have been developing new assays for chromosome movement in vivo and in vitro.

Robert Palmer, Koval, and Koshland have visualized chromosome segregation in living yeast using digital-imaging microscopy of fluorescently labeled chromosomes. They observed in normal cells several subtle features of chromosome movement previously observed in other eukaryotic cells, suggesting that the mechanisms of chromosome movement in yeast and higher eukaryotes are highly conserved. One particularly interesting observation was that the axis of chromosome segregation in yeast apparently undergoes a programmed rotation, probably due to rotation of the spindle. Similar observations have been made in cell divisions of higher eukaryotes. In addition, the analysis of chromosome movement in mutants that block the progression of chromosome segregation revealed unusual oscillation of chromosomes between the two halves of the dividing cell. One mutant failed to move its DNA at all. The gene identified by this mutant has been cloned by Eileen Hogan and is presently being sequenced to determine whether it shares homology with known microtubule motors important in the movement of other cellular organelles.

Jeff Kingsbury has been working on an assay for analyzing chromosome movement in vitro. As a first step, he has developed a technique for isolating small circular minichromosomes from yeast and has shown that these minichromosomes will co-precipitate upon centrifugation with microtubules (i.e., attachment has occurred) only when they contain a kinetochore. Co-precipitation does not occur in the absence of microtubules or when microtubules are disassembled. In addition, co-precipitation is dependent upon microtubule number. This in vitro assay for the binding of minichromosomes to microtubules will be used to address the regulation of kinetochore activity during the cell cycle, to identify genes whose products are required for kinetochore function, and to examine chromosome movement in vitro.

### *Lampbrush Chromosomes*

Joseph Gall's laboratory continues to be interested in oogenesis, with special emphasis on the relationship between structure and function in the oocyte nucleus, or germinal vesicle (GV). The GV of frog and salamander oocytes is the largest known nucleus, and the lampbrush chromosomes within it are the largest known chromosomes. For this reason, many cytological and biochemical

experiments that cannot be carried out with smaller nuclei are possible in this system.

During the past year Gall and his colleagues have examined the transport of proteins from their site of synthesis in the cytoplasm to their final destination within the GV. The aim has been to identify sequences necessary for appropriate subnuclear localization. In experiments begun before he left the Department in December 1988, Mark Roth injected synthetic messenger RNA into frog and newt oocytes; the RNA encoded a protein called SE5 that is localized on the lampbrush chromosome loops. Roth found that SE5 protein was produced from this messenger RNA, and that it was transported into the nucleus, where some of it ended up appropriately on the chromosome loops. Brenda Peculis has conducted more-extensive experiments with a nucleolar protein called NO38. Again by injecting synthetic messenger RNA into the oocyte cytoplasm, she found that the oocyte produced a large amount of the NO38 protein. Most of the newly synthesized protein entered the nucleus and about half found its way to the nucleoli. She also injected messenger RNAs truncated at their 3′ ends, and in this way identified a region of the molecule necessary for nucleolar localization. Her ultimate goal is to determine whether simple "nucleolar localization" signals exist, and if so, whether they can give insight into the mechanisms whereby nucleolar proteins reach the nucleoli.

Pat DiMario has concentrated on another nucleolar protein, which he designated GV95. GV95 was originally identified by its ability to bind single-stranded DNA on "Southwestern" blots. DiMario's interest in DNA-binding proteins came from the observation that the nucleoli and certain lampbrush chromosome loops differentially bind single-stranded DNA in cytological preparations. It is probable that GV95 is responsible for the DNA binding of nucleoli in such preparations. Recent experiments suggest that GV95 may be a previously characterized nucleolar protein called nucleolin.

Within the past few months Gall and colleagues have begun studies on the small nuclear ribonucleoproteins (snRNPs) of the GV. While surveying the ability of several antibodies to stain lampbrush chromosomes by immunofluorescence, they found one (Y12) that stained not only the chromosome loops but also the extrachromosomal structures known as "spheres" as well as thousands of smaller granules in the nucleoplasm. Y12 is a monoclonal antibody specific for several proteins associated wth snRNAs. Gall and colleagues next found that an antibody against trimethylguanosine gave the same pattern of staining as Y12. Since trimethylguanosine is a chemical group specific for snRNAs, their results showed that both snRNAs and at least some of their associated proteins are present in the lampbrush loops, the spheres, and many smaller intranuclear granules.

A visiting scientist from Beijing, Zheng'an Wu, has recently confirmed the localization of the snRNAs by carrying out in situ nucleic acid hybridization with a variety of snRNA-specific probes. Gall and his colleagues believe that the spheres may be sites for assembly of snRNP complexes, including perhaps components of the RNA-splicing machinery. (RNA is "edited" after it is transcribed, and the noncoding nucleotide sequences are spliced out.) Interest in the spheres is heightened by the fact that a few spheres are found attached to specific loci on the chromosomes. By analogy to the nucleolus and the nucleolus-organizing locus (NO), the site of sphere attachment is defined as the sphere-organizing locus (SO). An important unanswered question is the relationship of the attached spheres to the free spheres. The investigators predict that the sphere organelle and the SO will prove as important for the organization of nuclear ribonucleoproteins (snRNPs) as the nucleolus and NO are for the organization of cytoplasmic ribonucleoproteins (ribosomes). Studies on the snRNPs are also being conducted by postdoctoral fellow Michael Jantsch, visiting Professor H. G. Callan, and a recent graduate from the Johns Hopkins University, David Chang.

### *A Model Drosophila Chromosome*

Eukaryotic chromosomes must accurately reduplicate billions of nucleotide base pairs each cell generation, and transmit exactly one faithful copy of each chromosome to each daughter cell. A long-term goal in Allan Spradling's laboratory is to understand the molecular mechanisms that bring about accurate chromosome replication and transmission. Spradling and colleagues are also interested in how these processes have adapted to the specialized requirements within the many different types of cells of a complex organism. In their studies, they exploit the powerful genetic and molecular tools available with the fruitfly *Drosophila melanogaster.*

Experiments on gene amplification in the *Drosophila* ovarian cells that synthesize the eggshell were described in *Year Book 87* (pp. 24–27). The rapid replication of two eggshell gene clusters during oogenesis allowed postdoctoral fellow Margarete Heck to localize specific sites where replication actually begins on the third chromosome. This report will focus on a related set of experiments investigating the replication of an entire chromosome.

It is frequently useful in attempting to understand a problem to analyze it in the simplest possible form. Postdoctoral fellow Gary Karpen therefore turned to the smallest known *Drosophila* chromosome, called Dp1187, which despite its size replicates and separates to daughter cells much like other chromosomes. Dp1187 was

produced (in the 1950's) by removing 97% of the normal internal sequences from an X chromosome with x-rays; only the two ends of the original chromosome remained.

The DNA backbone of Dp1187 is correspondingly small. Work carried out in collaboration with staff associate David Schwartz revealed that Dp1187 contains only about 1.4 million base pairs, far fewer than any other known chromosome in a multicellular animal. Only about 300,000–400,000 of these base pairs are required to encode the ten known genes on the minichromosome. The remaining million base pairs are classified as "heterochromatin"—a large but little understood type of chromosome region found in almost all higher organisms. Heterochromatic regions are frequently associated with that portion of the chromosome thought to be necessary for separation to daughter cells, a process called "chromosome segregation." However, since heterochromatin contains highly repeated and scrambled DNA sequences but only rarely includes genes, it has been extremely difficult to study using either genetic or cloning methods. We have begun to apply genetic methods that use the *Drosophila* P transposon (described in previous reports) to remove specific portions of Dp1187 heterochromatin so that its functions can be tested directly.

Using pulsed electrophoresis, Karpen has constructed a map of most of the gene-containing portion of the minichromosome. He has been able to map over 100,000 base pairs of the heterochromatic region of the chromosome as well. Dp1187 is therefore well on the way to becoming the first chromosome of a multicellular organism to be completely mapped at the level of resolution used routinely in molecular biology—i.e., thousands of base pairs. Mapping the remaining heterochromatin still poses difficult technical problems. Nonetheless, enough information already has been obtained to allow Karpen to begin studying an interesting and long-standing problem in chromosome replication.

Many *Drosophila* cells, such as those of the larval salivary gland, undergo the specialized type of chromosome replication that produces the giant "polytene" chromosomes so useful to geneticists. During polytene replication the heterochromatic regions replicate much less than the remainder of the chromosome. Chromosome segregation and cell division cease, so that cells simply grow larger without increasing in number. Much as in the case of eggshell gene amplification, the differential replication of Dp1187 in salivary gland cells provides an opportunity to study how the replication of a specific chromosome region is regulated. Karpen has utilized his map of Dp1187 to investigate how replication proceeds along both the normal and heterochromatic parts of the minichromosome. His studies measured for the first time the extent to which replication decreases at the border of a heterochromatic region. Surprisingly, Karpen also discovered that the replication of Dp1187

varies from cell to cell within the salivary gland, and probably in many other adult tissues. His studies suggest that replication of heterochromatin may not always be as tightly controlled as replication of the coding part of chromosomes.

Karpen's findings may help explain a long-standing mystery in *Drosophila* genetics, termed "position-effect variegation." Genes that are relocated next to a heterochromatic region as the result of a chromosome rearrangement frequently are expressed only in some of the cells within a tissue. The expressing cells are scattered apparently at random throughout the affected tissues. Indeed, several of the genes on Dp1187 show typical position-effect variegation in flies with the replication defects we measured. Under conditions where the replication defects are suppressed, the variegated expression also disappears. Karpen and Spradling now believe that the random changes in the replication of Dp1187 are related to the random variegated expression of genes located near heterochromatin following chromosome rearrangement.

### *Proteins that Regulate Genes*

Steven McKnight and his colleagues continue to focus on proteins that regulate gene expression in mammalian cells. One of these proteins, viral protein 16 (VP16), is encoded by herpes simplex virus (HSV). VP16 is synthesized late during the lytic infectious cycle of HSV. About 1000 molecules of VP16 are incorporated into newly formed virus particles. When a virus enters a newly infected cell, VP16 activates the expression of the earliest temporal class of viral genes (termed immediate early, or IE, genes).

Each of the five HSV IE genes responds to activation by VP16 through a specific set of DNA-sequence elements. These elements, termed IE cis-response elements, represent binding sites for cellular proteins. VP16 becomes associated with viral IE genes indirectly. Instead of binding directly to DNA, VP16 "piggy-backs" itself onto other proteins that bind to IE cis-response elements. Once associated with an IE gene, VP16 donates a negatively charged polypeptide segment that somehow activates transcription.

In an effort to dig deeper into the mechanism of VP16-mediated gene activation, Kelly LaMarco has purified one of the cellular factors that binds directly to IE cis-response elements. This factor, termed IE facilitator (IEF), appears to be composed of several protein chains. Efforts are underway to obtain partial amino acid sequences of the polypeptides that confer IEF binding activity. This information will be helpful for generating antibodies and cDNA clones. It is hoped that the development of these molecular reagents will provide clues to the mechanism of VP16 action, and, perhaps, help unveil circuits of cellular gene expression that are coordinately controlled by IEF.

Similar studies have been carried out on a second transcriptional regulatory protein, termed CCAAT/enhancer binding protein (C/EBP). Several years ago Barbara Graves, Peter Johnson, and Bill Landschulz succeeded in purifying C/EBP and in isolating the gene that encodes it. Using the information and reagents derived from initial studies of C/EBP, they have begun to uncover information relevant to its physiologic role and mode of DNA binding. As reported in *Year Book 87* (pp. 42–44), C/EBP utilizes a new DNA binding motif termed the "leucine zipper." This is a bipartite motif that makes use of a dimerization interface (the zipper) and a DNA contact surface (the basic region). Peter Agre, a visiting scientist from Johns Hopkins University Medical School, and Johnson have conducted experiments showing that the basic region confers DNA-binding specificity. Charles Vinson has extended protein modeling studies on C/EBP, and Jon Shuman, in experiments being conducted in collaboration with Paul Sigler of Yale University, is in the process of crystallization trials. The goal of Shuman's studies is to obtain x-ray diffraction patterns that will lead to a resolution of the atomic structure of C/EBP.

Experiments have also been aimed at identifying the physiologic role of C/EBP in mammals. In experiments conducted in collaboration with Ed Birkenmeier of the Jackson Laboratory, Landschulz has found that C/EBP mRNA is restricted to tissue and cell types that metabolize lipids at unusually high rates. Alan Friedman and Landschulz have shown that C/EBP is a direct regulator of the gene that encodes the major lipid carrier protein of serum (albumin). Similar studies have been carried out by Birkenmeier on the gene that encodes glycerol-6-phosphate dehydrogenase, and by M. Daniel Lane, Thomas Kelly, and their colleagues at the Johns Hopkins University Medical School on two genes that are expressed selectively in differentiated fat cells. These observations raise the possibility that C/EBP provides certain differentiated cells the capacity to metabolize lipids at unusually high rates.

### *Control of Cellular Differentiation in the Nematode C. elegans*

A newborn nematode of species *C. elegans* has only 558 cells, but among these are many of the cell types seen in higher organisms. The laboratory of Andrew Fire uses *C. elegans* to study signals which allow some cells to become muscles. Initially, Fire and his colleagues have concentrated on four genes that encode myosin, a major structural protein in muscle. Two of these genes (myoA and myoB) are expressed in the body wall muscles used for locomotion, and two (myoC and myoD) are expressed in pharyngeal muscle used in eating.

Two kinds of assay have been used to study gene regulation; both involve micro-injection of DNA into oocytes. (1) DNA segments containing the myoB gene are introduced into a paralyzed mutant strain lacking myoB. If the injected genes are expressed, then the muscle defects in the mutant strain are remedied, allowing normal movement. (2) Gene fusions are constructed by replacing myosin protein-coding sequences with sequences encoding an enzyme not normally present in *C. elegans*. Expression can be analyzed by introducing the fusion genes into the nematode followed by localizing the novel enzyme activity with a chemical stain.

The myoB gene has been the most extensively analyzed, using both types of assay. Sequences critical for expression lie at both ends of the transcribed region and within introns. Introns are non-coding regions within genes whose origin and general function remain unknown. The introns in myoB contribute to expression in two ways. The first is a nonspecific stimulation given by an intron near the beginning of the transcript. This can apparently be satisfied by any functional intron (including introns entirely foreign to the nematode). Mutational analysis is being used to determine whether this first component of the intron requirement reflects an interaction between nascent RNA and the splicing apparatus.

A second component of the myoB intron requirement results from a single segment (an "enhancer") within intron 3. Enhancers are DNA segments which can act at considerable distances to stimulate expression of genes on the same DNA molecule. When moved around, the myoB enhancer can stimulate a variety of different genes to express in body wall muscles.

A region just upstream of the myoB coding region (the myoB "promoter") is also involved in tissue-specific expression. The high level and specificity of myosin expression from the intact gene apparently reflects contributions from both upstream "promoter" and internal "enhancer" segments, although each alone is sufficient to confer expression in the proper tissues.

Analysis of two other myosin genes have provided further examples of tissue-specific regulation. Tissue specificity of the myoA gene results from three enhancer regions, each active in body wall muscle. Signals mediating pharyngeal expression of the myoC gene have been mapped to a short region which exhibits both enhancer and promoter activities. Tissue specificity for the myosin promoters apparently requires at least two positively acting factors: one muscle-specific promoter element can be activated in either body wall or pharyngeal muscle, while a second element determines muscle type specificity.

The identification of DNA-sequence elements involved in myosin regulation should allow isolation of the protein factors which interact to mediate muscle specific expression. The mechanism

whereby these factors are themselves restricted to muscle cells should, in turn, illuminate the mechanism of cellular differentiation.

All cells have the machinery to carry out recombination events—the breaking and rejoining of two DNA molecules in regions of similarity. This process has allowed biologists to produce directed and precise genetic changes in several unicellular organisms, and to study the effect of these changes in vivo. Similar gene-replacement systems are currently being developed for higher organisms in order to study problems of organismal development. Fire and colleagues have initiated an analysis of recombination following microinjection of DNA into *C. elegans.* An active system allows homologous recombination between injected DNA molecules. Although *C. elegans* chromosomes rarely recombine with the injected DNA, two transformed lines resulting from homologous recombination between injected and chromosomal sequences have been obtained. Future experiments will concentrate on increasing the occurrence of recombination, and on genetic schemes to select for specific recombination events.

*Amphibian Metamorphosis*

It has been known for 75 years that the thyroid gland is essential for tadpoles to metamorphose into frogs. The active ingredient is the well-known hormone thyroxine. Donald Brown and his colleagues have begun a study of this remarkable developmental event, in which just about every tissue of the tadpole is changed and remodeled over a period of a few weeks. How can one simple hormone induce so many dramatic changes? Brown's group would like to understand the cascade of molecular events that are begun by thyroxine.

The first step has been to identify the intracellular receptor molecules that thyroxine binds to when it enters a cell. Thyroid receptors were discovered simultaneously in humans and chickens about three years ago by scientists in California and in Europe. Using a gene for a human thyroid receptor (generously provided by Ronald Evans, Salk Institute), Yoshio Yaoita has successfully identified homologous *Xenopus* genes. There are at least three different genes for thyroid receptors in *Xenopus*, and they are remarkably similar to their human and chicken counterparts. This attests to the conservation throughout vertebrate evolution of these important genes and, of course, of the protein receptors that they encode. Yun-bo Shi has begun a comprehensive search for genes that are activated or repressed at metamorphosis as a response to thyroxine. Such genes are called thyroid-response genes. From the global nature of the morphological and biochemical changes, there are presumed to be many such genes.

A project that developed from Brown's long-term study of the 5S

RNA genes has been the identification of a protein related to TFIIIA, the positive transcription factor that activates the *Xenopus* 5S RNA genes. TFIIIA has nine zinc fingers that comprise the DNA- and probably the RNA-binding site of the protein. The related protein, which has nine similar zinc fingers, also binds 5S RNA—but not 5S DNA. Keith Joho has sequenced the gene for TFIIIA and for the related protein from two species of *Xenopus*—*X. laevis* and *X. borealis*. He and Martyn Darby are analyzing the features of this protein that cause it to bind exclusively to RNA, comparing them to features enabling the closely related protein TFIIIA to bind both DNA and RNA.

*Transposable Elements of Maize*

During the past year, Nina Fedoroff and her colleagues have continued to focus on the molecular genetic analysis of the maize *Suppressor-mutator* (*Spm*) transposable element. Using a newly developed assay, they analyzed the *Spm* element's genetic organization by introducing genetic changes (mutations) into a cloned copy of the element and then testing the effects of the mutations on the activity of the element in transgenic tobacco cells. They have also continued their studies on the epigenetic control of *Spm* expression during development.

Last year, postdoctoral fellow Patrick Masson developed a system for testing the activity of the *Spm* element in tobacco cells. The *Spm* element is introduced into tobacco cells together with a molecular construct consisting of a bacterial β-glucuronidase (GUS) gene expressed from a plant promoter but whose expression has been interrupted by the insertion of a transposition-defective *Spm* (*dSpm*) element. The *Spm* element and the *dSpm*-containing GUS gene are carried into the easily manipulated tobacco cells on a plasmid in the bacterium *Agrobacterium tumefaciens*. This bacterium contains the genetic information for transferring the plasmid DNA to the plant cell.

Once inside the tobacco cells, the *Spm* element is expressed and produces the element-encoded gene products required for transposition of the *dSpm* element out of the GUS gene. Transposition occurs in some cells, reconnecting the GUS gene with its promoter and permitting it to be expressed. This event, in turn, is detectable with a chromogenic substrate for the β-glucuronidase enzyme. Transposition occurs in some cells, but not in others, resulting in tobacco leaves and plantlets with blue-staining sectors.

Using this assay system, Masson discovered that small mutations in a part of the element previously believed to be an inert, so-called intervening sequence, or intron, were able to disrupt its function. These observations opened the possibility that the *Spm* element's genetic organization was more complex than previously

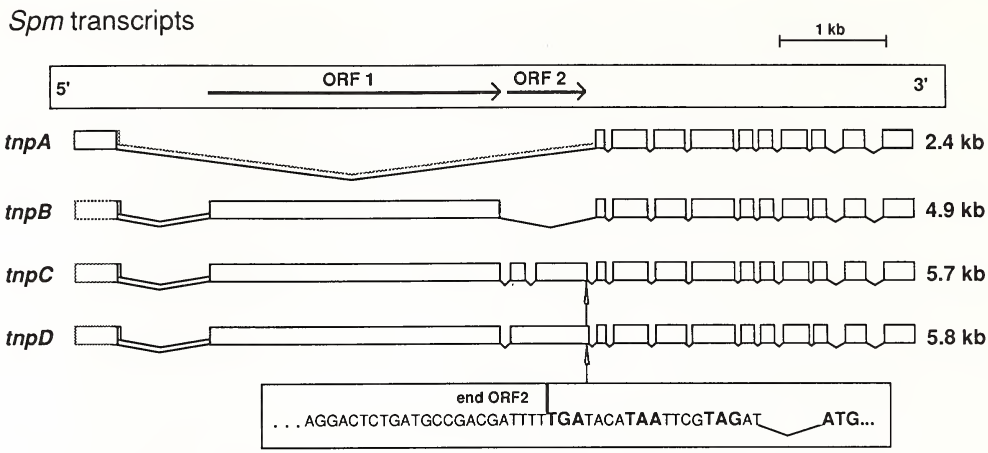


Fig. 2. The structure of several *Spm* mRNAs. The *Spm* element is represented by the open box, its transcriptional orientation is indicated, and the ORFs of *tnpA* intron 1 are represented by arrows. The diagrams below the element show the proposed exon/intron structure of the *tnpA*, *tnpB*, *tnpC*, and *tnpD* transcripts; their lengths, exclusive of the polyA tract and the 126-bp sequence between the alternative exon 1 donor sites, are given at the right of each diagram. Exon 1 is represented by broken lines in the large transcripts because the location of the transcription start site has not been directly determined. The alternative splice donor sites at the end of exon 1 are represented by the two overlapping exon 1 blocks in each diagram; a broken line has been used to connect the second donor site with exon 2 in the *tnpA* diagram because of the low frequency with which this site is used in maize *tnpA* transcripts. The sequence at and following the end of ORF2 is shown in the block at the bottom of the diagram.

thought; Masson, postdoctoral fellow Jody Banks, and technician George Rutherford therefore began a search for additional messenger RNAs (mRNAs) encoded by the element. The *Spm* element is now known to encode at least four different large mRNAs, all derived from the same primary transcript (Fig. 2). All appear to have the same first exon (coding region) and last ten exons as the previously identified major transcript (called *tnpA*), but the three additional mRNAs are much longer and have one, two, or three additional exons derived from intron 1 sequences of the *tnpA* gene. In addition, two alternative splice donor sites have been identified at the end of exon 1, and at least the *tnpA* transcript and possibly all of the transcripts exist in two alternative forms, depending on which splice donor site is used during splicing.

These results bear the strong implication that element expression is regulated at the level of differential splicing and translation. They also suggest that the element's genetic functions reside in protein isoforms translated from alternatively spliced mRNAs derived from the same primary transcript. An immediate objective is to determine the function of each of the newly identified mRNAs.

In other studies, Jody Banks continued her analysis of the element's transcriptional control mechanism. During the past year, she has found that the differential genetic expression of the element in different plant parts is highly (although not perfectly) correlated with the levels of methylation of sites upstream of its transcription start site. (Methylation is the addition of a methyl group at sites along a DNA molecule.) As in previously reported experiments, the stability of the element's inactive state depends on the extent to which a GC-rich sequence downstream from its transcription start site is methylated. Banks found that different parts and tissues of the same plant could differ markedly in the extent of element methylation. She concluded that the methylation-associated inactivation system is highly dynamic, undergoing marked changes at several points during plant development.

*Plant Geminiviruses*

Geminiviruses are economically important plant pathogens. Their very small genomic size and host range properties make these viruses excellent models for the molecular analysis of virus-host interactions and the regulation of gene expression in both monocotyledonous and dicotyledonous plants. Sondra Lazarowitz has continued to investigate the gene functions essential for disease development and host-range variation using the African maize streak virus (MSV, a single genome virus) and squash leaf curl virus (SqLCV, a bipartite genome virus). The latter is agronomically important in Central America and the U.S. Southwest.

Using site-directed mutagenesis, she completed the first molecular genetic analysis of a single component geminivirus (MSV). In this work, she and her colleagues devised a unique approach to the construction of gene-substituted viral genomes in which the desired gene replacements were generated in maize plants following *Agrobacterium*-mediated inoculation. This has provided new information concerning the agroinoculation procedure, which is important in current plant transformation strategies. The studies established that excision of the viral genome from the binary vector on which it is introduced into the plant occurs by homologous recombination within flanking copies of any repeated sequence, rather than by a replication-mediated event. She also identified the functional existence of the small viral R2 gene, demonstrating that it, as well as the capsid gene sequences, was essential for systemic movement in the plant and the development of plant cytopathology. The functions essential for viral replication were localized to a small 1.6-kb segment of the viral genome which contains the two viral intergenic regions and sequences homologous to the gene essential for replication in the bipartite geminiviruses. This work has therefore established a distinction between the

single genome and the bipartite genome geminiviruses, namely that the capsid sequences are essential for systemic movement in the former whereas they are dispensable in the latter. It further identified similarities in their genetic organization, with both viruses encoding multiple essential functions for systemic movement and disease development, as well as containing their essential replication functions in homologous regions of the genome.

Analysis of SqLCV has elucidated the role of viral replication and movement in the generation of host-range variation in these bipartite geminiviruses. Using two closely related viral strains (SqLCV-E and SqLCV-R) identified in diseased field squash, Lazarowitz identified a defect in replication associated with the different host-range properties of these viruses. SqLCV-R was shown to replicate less efficiently in restrictive hosts than in permissive hosts. This replication defect in certain hosts could be trans-complemented by the genome of SqLCV-E, thus accounting for the unorthodox pattern of SqLCV-R transmissions observed in the field. The difference in ability of SqLCV-R and SqLCV-E to replicate in discriminating host plants appears to be associated with a 13-base deletion in SqLCV-R located next to the only viral gene essential for replication (AL1), thus possibly altering the gene's expression.

Lazarowitz also identified a defective genomic component of SqLCV-R. This defective component does not cause disease in tobacco, a normally permissive host, although it does result in disease when inoculated into other hosts such as squash and pumpkin. The lack of infectivity in tobacco was not due to an inability to replicate, demonstrating that this component has a host-dependent defect affecting expression of a viral gene essential for movement. This molecular genetic analysis of SqLCV has delimited viral genomic sequences important for a variety of viral functions. The next step will be the identification of host cell factors that regulate gene transcription and influence the ability of the virus to move within the plant and thus cause disease.

*News of the Department*

It is with great pleasure that we announce the appointment of Andrew Fire as a new staff member. He replaces Sam Ward, who moved to the University of Arizona last year. Fire, like Ward, studies the nematode *C. elegans*. While a postdoctoral fellow at the Medical Research Unit in Cambridge, Fire developed a method to introduce foreign genes into *C. elegans*, thereby greatly extending its utility for genetic studies. His Ph.D. research at MIT made important contributions to the biochemistry of gene expression in animals. His current research analyzes certain muscle genes and their tissue-specific expression in *C. elegans*.

Honors to our staff and students are listed elsewhere in this volume (p. 12). We shared our pride with them one day in June when we celebrated our honorees and their families.

The Department holds weekly seminars. Members of the Baltimore-Washington scientific community are invited to participate. The Department hosted its Twelfth Annual Carnegie Minisymposium, entitled "Post-Transcriptional Modes of Gene Regulation," on Thursday, November 17, 1988. The speakers were Richard Klausner (National Institutes of Health), Martin Low (Columbia University), Alan Hinnebusch (National Institutes of Health), Kenneth Stuart (Seattle Biomedical Research Institute), David Beach (Cold Spring Harbor Laboratory), and Bruce Baker (Stanford University).

Support of research in the Department comes from a variety of sources. Steven McKnight and Allan Spradling are employees of the Howard Hughes Medical Institute. We are grateful recipients of individual grants from the National Institutes of Health, the Leukemia Society of America, the American Cancer Society, the National Science Foundation, the Jane Coffin Childs Memorial Fund, the Helen Hay Whitney Foundation, and the John D. and Catherine T. MacArthur Foundation's program in parasitology. A grant to purchase small instruments and a Biomedical Research Support Grant to the Department from the National Institutes of Health are gratefully acknowledged. We remain indebted to the Lucille P. Markey Charitable Trust for their support.

*—Donald D. Brown*

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## The Golgi Apparatus: Insights from Lipid Biochemistry

**by Richard E. Pagano**

The Golgi apparatus, since its discovery in 1898, has fascinated cytologists because of its distinct morphology. This organelle consists of flat cisternae—fluid-containing sacs—arranged in parallel to form characteristic "stacks" often encircling the cell nucleus, interconnected by cisternal or tubular-reticular bridges (see Fig. 1). Four areas, the *cis*, *medial*, *trans*, and *transmost* subsections, can be seen. (In some cell types, the *cis* is situated closest to the nucleus and the *transmost* is the most distant.) From biochemical studies we now know that the Golgi apparatus has at least three functionally distinct compartments, which operate sequentially to build the oligosaccharide chains on transported glycoproteins and to "sort out" proteins destined for transport to other regions of the cell (e.g., the lysosomes, cell surface, or secretory granules). Currently the focus of much attention among

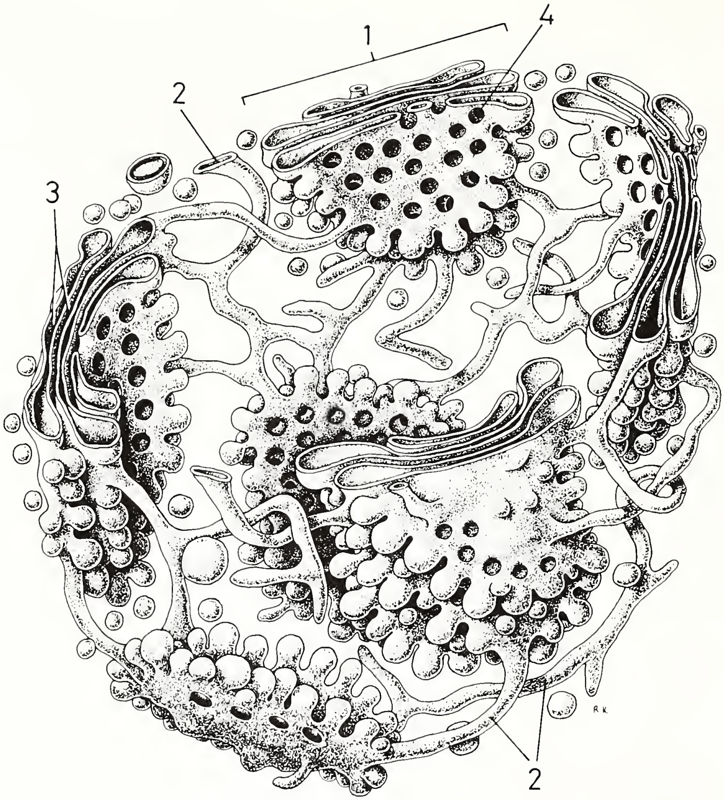


Fig. 1. Three-dimensional representation of the Golgi apparatus. In transverse section, the Golgi apparatus is seen as stacks of interconnected flattened cisternae (*1*). Together these often encircle the cell's nucleus. Branching tubules (*2*) connect Golgi cisternae (*3*), creating a complex network. Note the numerous pores (*4*) on the inner surface of the Golgi. From Radijov V. Krstic, *Ultrastructure of the Mammalian Cell: An Atlas*, Arthur R. Von Hochstetter, tr., Springer-Verlag, New York, 1979 (drawing by W. Bargmann).

cell biologists, the Golgi apparatus challenges us with many fundamental and as yet unanswered questions. Until now, most biochemical and cell biological studies of the Golgi apparatus have concentrated on its role in glycoprotein synthesis and sorting. However, the studies from our laboratory highlighted here indicate that this remarkable organelle also plays an important role in lipid synthesis and transport.

*A Vital Stain for the Golgi Apparatus*

For a number of years, our laboratory has systematically studied the synthesis and transport of lipid molecules in animal cells. Our goal is to define the pathways and molecular mechanisms whereby the many different lipid species found in cells move from one organelle to another. This is a fundamental problem in membrane biology, one difficult to study because simple techniques

for examining lipid "traffic" within cells have not been available. We developed a new approach using a series of fluorescent lipid molecules synthesized in our laboratory. In our early studies we found that when the various analogs were incubated with cells, they were metabolized similarly to their endogenous counterparts. Because the molecules were fluorescent, we were able to examine their distribution within *living* cells by high-resolution fluorescence microscopy, and to correlate changes in intracellular distribution with lipid metabolism. The observed metabolism of these molecules was particularly significant because it demonstrated that even though the lipids we synthesized were fluorescent and therefore "non-natural," they were recognized by the enzymes involved in lipid metabolism and translocation.

Our interest in the Golgi apparatus began in 1981 when Naomi Lipsky joined the laboratory as a postdoctoral fellow. I suggested that she synthesize a fluorescent analog of ceramide, N-($\epsilon$-NBD-aminocaproyl)-D-*erythro*-sphingosine, or $C_6$-NBD-Cer, and study its behavior in cells. This analog was potentially interesting because endogenous ceramide is a key intermediate in sphingolipid biosynthesis—it is metabolized to sphingomyelin, a major structural lipid, and to glycolipids and gangliosides, relatively minor lipids which play important roles in cell function (e.g., cell-cell recognition).

In our initial studies using Chinese hamster fibroblasts, we found that when cells are treated with $C_6$-NBD-Cer at low temperature and washed, the endoplasmic reticulum, nuclear envelope, and mitochondria become fluorescently labeled. Upon warming the cells to 37°C, the fluorescent ceramide is metabolized to fluorescent sphingomyelin (SM) and glucosylceramide (GlcCer); concomitantly, the Golgi apparatus becomes intensely fluorescent. After further time at 37°C, the plasma membrane also becomes visibly labeled as fluorescent SM and GlcCer are transported to the cell surface. Transport of these newly synthesized fluorescent sphingolipids to the plasma membrane is inhibited in mitotic cells and by the ionophore Monensin; likewise inhibited under these conditions is the movement of newly synthesized glycoproteins to the cell surface. These results indicate that the fluorescent SM and GlcCer analogs are synthesized intracellularly and then transported from the Golgi apparatus to the plasma membrane by a vesicle-mediated process analogous to the movement of plasma-membrane and secretory proteins between the Golgi apparatus and the plasma membrane.

In a study published in 1985, Lipsky and I showed that $C_6$-NBD-Cer prominently stained the Golgi apparatus of several different cell types and was thus a vital stain for this organelle. Since then we have used the lipid on many cell types; in every case we found prominent labeling of this unique organelle. To our knowledge, $C_6$-NBD-Cer is the only known vital stain for the Golgi apparatus. As a result, many laboratories engaged in various cell biological

studies of the Golgi apparatus have used $C_6$-NBD-Cer as a tool in their studies. One particularly intriguing study is being carried out by M.S. Cooper and colleagues at Yale University. Using $C_6$-NBD-Cer and fluorescence video imaging, they have studied the dynamics of the Golgi apparatus in living cells and have provided evidence that the Golgi apparatus rapidly forms tubulovesicular extensions along microtubules. It is not yet known whether these processes are involved in transport of materials among the various Golgi subcompartments or from the Golgi apparatus to other organelles.

*The Golgi Apparatus as a Molecular Trap for Ceramide*

The labeling of the Golgi apparatus by $C_6$-NBD-Cer is so highly specific and striking that we decided to investigate further the mechanism whereby $C_6$-NBD-Cer initially accumulates at the Golgi apparatus. Control experiments showed that Golgi labeling is specific for ceramide and is not simply due to the presence of the fluorescent probe. One possibility is that the fluorescent lipid, and perhaps its metabolites, are transported to the Golgi apparatus

Fig. 2. Accumulation of $C_6$-NBD-Cer at the Golgi apparatus of fixed cells. Human skin fibroblasts were fixed with glutaraldehyde, washed, incubated with $C_6$-NBD-Cer, and then back-exchanged with bovine serum albumin prior to observation and photography. Bar represents 10 μm.

by an energy- and temperature-dependent process analogous to that seen for the delivery of newly synthesized proteins from the endoplasmic reticulum to the Golgi apparatus. Alternatively, $C_6$-NBD-Cer labeling might be due to binding of the fluorescent lipid to enzymes in the Golgi apparatus involved in ceramide metabolism, or the lipid might preferentially partition into this organelle as a result of some special "physical property" of the Golgi membranes. In our initial attempts to distinguish among these possibilities, we were unable to inhibit $C_6$-NBD-Cer labeling of the Golgi apparatus at low temperatures or in the presence of various metabolic inhibitors. Surprisingly, labeling of the Golgi apparatus even occurred in cells which had been fixed with glutaraldehyde *prior to* incubation with the fluorescent lipid.

Recently Ona Martin, Mike Sepanski, and I have characterized $C_6$-NBD-Cer labeling of the Golgi apparatus of fixed cells and obtained evidence that the membranes of this organelle function as a molecular trap for $C_6$-NBD-Cer. When cells are fixed with glutaraldehyde and subsequently incubated with $C_6$-NBD-Cer, labeling of the Golgi apparatus is detected, but it is difficult to see clearly because of a high "background" from other fluorescently labeled intracellular membranes within the treated cells. However, this background fluorescence can be removed when the labeled cells are further incubated ("back-exchanged") with defatted albumin. The result is a preparation of fixed cells in which only the Golgi apparatus is visibly stained by $C_6$-NBD-Cer (Fig. 2).

We also developed a method for visualizing $C_6$-NBD-Cer in fixed cells under the electron microscope (EM). In this procedure, $C_6$-NBD-Cer–labeled cells are irradiated in the presence of diaminobenzidine (DAB). During irradiation, the fluorophore is photobleached and the photooxidation products catalyze the polymerization of DAB. This results in an electron-opaque osmiophilic polymer which appears black under the EM and is present at sites within the specimen which were originally labeled by the fluorescent lipid. As shown in Fig. 3, this procedure localizes $C_6$-NBD-Cer to only one or two stacks of the Golgi apparatus, although numerous small vesicles were also labeled in some sections, possibly resulting from tangential sections through the Golgi cisternae. Using other markers for known subcompartments of the Golgi apparatus in double label experiments, we have determined that $C_6$-NBD-Cer labeling is restricted to the *trans*-Golgi cisternae.

Several pieces of evidence suggest that the trapping of $C_6$-NBD-Cer at the Golgi apparatus of fixed cells is due to its interaction with Golgi membrane lipids. First, accumulation of $C_6$-NBD-Cer occurs in cells fixed in a variety of ways, but this accumulation is inhibited when fixation protocols which extract or modify cellular lipids are used. For example, glutaraldehyde-fixed cells

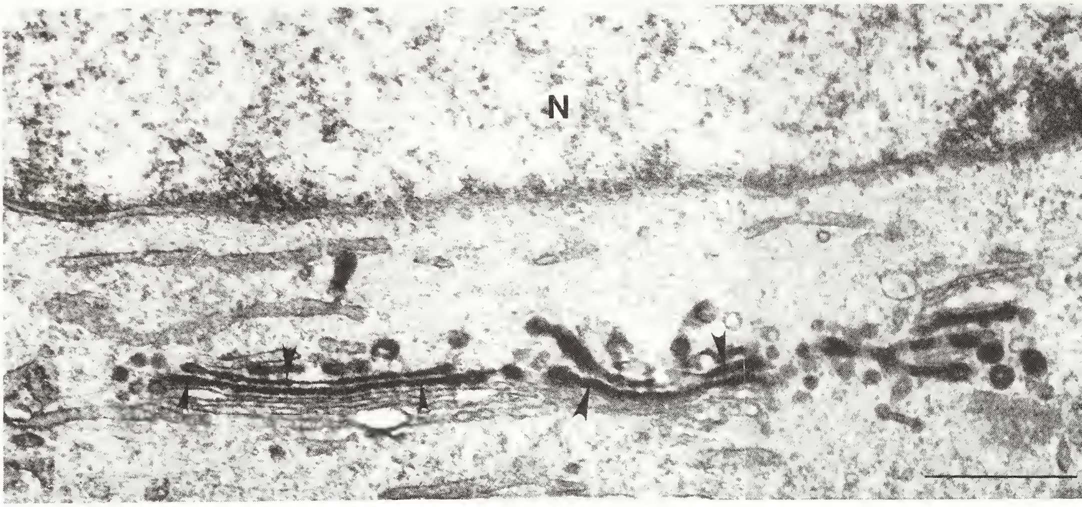


Fig. 3. EM localization of $C_6$-NBD-Cer at the Golgi apparatus of fixed cells. Chinese hamster ovary cells cells were fixed, incubated with $C_6$-NBD-Cer, and back-exchanged to give prominent labeling of the Golgi apparatus. The cells were then photobleached in the presence of DAB, washed, treated with $OsO_4$, and processed for electron microscopy. Black deposition product at arrows represent sites of $C_6$-NBD-Cer localization in the fixed cells. *N*, nucleus. Bar represents 0.5 μm.

rendered permeable by brief treatment with detergents and then washed extensively do not exhibit post-fixation staining of the Golgi apparatus by $C_6$-NBD-Cer, although such treatments have no obvious effect on Golgi morphology seen at the level of the light microscope with fluorescent antibodies. Second, quantitation of the amount of $C_6$-NBD-Cer present after back-exchange indicates that 1.0–4.2 $\times$ $10^8$ molecules of the fluorescent lipid are present at the labeled Golgi cisternae of each cell. Therefore $C_6$-NBD-Cer labeling of the Golgi apparatus is probably not due to its binding to a resident Golgi protein or proteins, since the required number of copies of protein would be extraordinarily high. Finally, Filipin, a fluorescent polyene antibiotic which forms complexes with cellular cholesterol and labels the Golgi apparatus of fixed cells, inhibits accumulation of $C_6$-NBD-Cer at that organelle.

Recently, in collaboration with Drs. Peter Pentchev and Joan Blanchette-Mackie of the National Institutes of Health, we have begun to explore how alteration of cellular cholesterol affects accumulation of $C_6$-NBD-Cer at the Golgi apparatus. We found that growth of cells in delipidated serum or in medium containing inhibitors of cholesterol biosynthesis modified the cholesterol content of the Golgi apparatus and eliminated $C_6$-NBD-Cer labeling (Fig. 4). Golgi labeling could be restored by stimulating endogenous cholesterol biosynthesis using mevalonic acid, a precursor of choles-

terol biosynthesis, or by supplying exogenous cholesterol to the growth medium. These striking and unexpected results suggest that the sterol content of the trans-Golgi cisternae plays a critical role in $C_6$-NBD-Cer labeling. However, since cholesterol is also present in other cellular membranes to which $C_6$-NBD-Cer does not localize, we speculate that other Golgi membrane lipids are also involved in the molecular trapping of $C_6$-NBD-Cer.

### *Metabolism of Ceramide to Sphingomyelin Occurs at the Golgi Apparatus*

Sphingomyelin (SM) is synthesized in mammalian tissues from ceramide by the transfer of phosphorylcholine directly from phosphatidylcholine (PC):

$$\text{PC} + \text{ceramide} \rightarrow \text{SM} + \text{DAG},$$

generating a molecule of diacylglycerol (DAG) for each molecule of SM formed. While the biochemical pathway leading to SM synthesis is established, the intracellular site of SM biosynthesis is

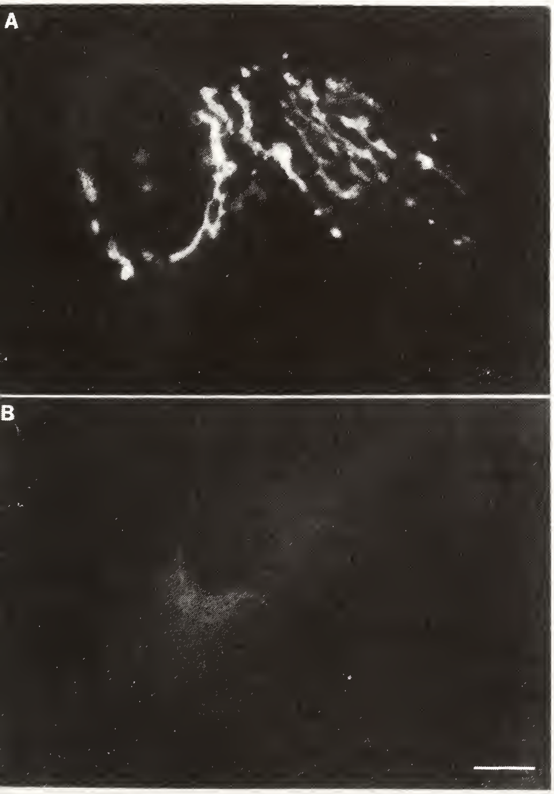


Fig. 4. Effect of cholesterol content on $C_6$-NBD-Cer labeling of the Golgi apparatus. Human skin fibroblasts were grown in culture medium containing (A) 10% fetal bovine serum or (B) 10% lipoprotein-deficient serum. The cells were then incubated for 30 min at 2°C with $C_6$-NBD-Cer, washed, and warmed for 30 min at 37°C prior to photography. Bar represents 10 μm.

not known, although circumstantial evidence suggested that SM synthase activity was localized at the plasma membrane, Golgi apparatus, or both. Because SM synthesis could play an important role in maintaining the lipid composition of the organelle where it is synthesized, we decided to rigorously determine the intracellular site of SM synthesis. This work was performed by Tony Futerman, a postdoctoral fellow in the laboratory, in collaboration with Drs. Ann Hubbard and Bruno Steiger of the Johns Hopkins School of Medicine. Well-characterized subcellular fractions were isolated from rat liver and incubated with a radiolabeled analog of ceramide. The synthesis of radioactive SM was quantified in various subcellular fractions. Using a Golgi fraction which was highly enriched in a Golgi marker enzyme, galactosyl transferase, and which showed very little cross-contamination with other subcellular compartments, we found an 84-fold enrichment of SM synthase activity. Small amounts of SM synthase activity were associated with enriched plasma membrane and rough microsome fractions, but after accounting for the contamination of these fractions by Golgi membranes, they together contributed less than 10–20% of the total SM synthase activity in liver. Thus we conclude that at least 80–90% of SM synthesis in rat liver is associated with the Golgi apparatus.

We have further separated the Golgi membranes into fractions of heavy, intermediate, and light density using an established procedure. These various fractions result from the fact that as nascent lipoproteins mature through the Golgi complex and acquire lipid, they become lighter in density. As a result, Golgi fractions from *trans* cisternae are lighter in density than those obtained from *cis* and *medial* cisternae. When these fractions were assayed for SM synthase activity, synthesis was readily seen in the heavy and intermediate, but not in the light Golgi membranes. These data suggest that SM synthesis occurs in a subset (*cis* and *medial*) of Golgi compartments. This conclusion is supported by our earlier studies using $C_6$-NBD-Cer in cultured fibroblasts where we found that the ionophore Monensin does not interfere with the synthesis of SM from ceramide, but does inhibit the transport of the newly synthesized SM to the plasma membrane. Since Monensin has been shown to block *medial*-to-*trans* movement of glycoproteins, this result suggests that SM synthesis occurs in early compartments of the Golgi apparatus.

Our studies demonstrating that $C_6$-NBD-Cer preferentially labels the *trans* Golgi of (fixed) cells, while metabolism to SM occurs in the *cis* and *medial* Golgi elements, present us with a paradox in that the lipid substrate is delivered distal to the compartment(s) where it is metabolized. One possible explanation for this may be that ceramide undergoes retrograde transport within the Golgi apparatus during SM synthesis.

*Future Directions*

Our studies with fluorescent and radioactive analogs of ceramide have yielded a vital stain for the Golgi apparatus and established this organelle as the major site for sphingomyelin biosynthesis. The next phase of our studies will focus on (1) isolating and purifying the Golgi enzyme responsible for SM synthesis, (2) determining the direction of ceramide transport within the Golgi stacks, and (3) studying the interrelationship of cholesterol biosynthesis and sphingolipid metabolism in cells. We hope that these studies will provide useful insights on how lipid and protein sorting and translocation through the Golgi apparatus are interrelated and controlled.

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## *The Director's Essay*

A director of one of the Carnegie Institution of Washington's five departments must cope with an annually recurring dilemma: Which of the many productive investigations merit inclusion in the director's annual essay? The selection process, of necessity based on a number of premises not always related to the overall importance of the work, tends to be somewhat capricious. For example, solid progress in long-term projects may be of considerable importance, but may not produce exciting copy for the reader. Investigations of great complexity are difficult to describe meaningfully in the few paragraphs allowed. Likewise a great deal of fine work has not yet developed to the point that hypotheses have been critically tested and broad conclusions derived. Finally, there are many more research projects of interest than can possibly be considered in an essay restricted to the Year Book's space limitations. The reader should keep these limitations in mind in reading the following paragraphs, which neglect a great deal of fine scientific accomplishment.

### *Plants and Their Environments*

In the best of all possible worlds, a plant harvests and utilizes a major fraction of the light energy incident on its leaves. Photons are captured by two complex pigment-protein associations known as Photosystems I and II, and their energy is transferred to electrons. The energized electrons can dissipate their acquired energy either through an elaborate system that synthesizes high-energy phosphate bonds (the common energy currency on which all life depends) or by reducing carbon dioxide to glucose (the common chemical currency that forms the basis throughout the living kingdom for energy storage).

Life, however, is not always perfect. Under conditions of drought, for example, higher plants close their stomata to restrict water loss. These tiny pores in the surfaces of leaves and stems are also the principal avenues by which most of the carbon dioxide enters to reach the chloroplasts, where photosynthesis takes place. Hence

closure of stomata also sharply curtails carbon dioxide availability. The rate of arrival of photons, naturally, is quite independent of drought, and a crisis situation develops: there is an excess of energized electrons, with no carbon dioxide to reduce. The electron transport pathway becomes filled to overflowing, and the energy must somehow be dissipated elsewhere. There are several possible reactions that will produce highly toxic products, such as hydroxyl radicals or superoxide (oxygen molecules with an extra electron), all of which can do severe damage to the photosynthetic machinery that generated the excited electrons in the first place.

Since plants do survive under drought and other stressful conditions leading to curtailment of photosynthesis, it is of great interest to understand the mechanisms they have evolved to cope with less-than-perfect environment. David Fork and Olle Björkman have long-standing interests in ferreting out these mechanisms, and both made significant progress in the past year. They use very different plant materials and very different approaches, with the result that we at the Department are developing a multidimensional understanding of the ways in which different plants protect themselves from high light stress.

Fork's current approach is strongly biophysical, employing an ingenious technique known as photoacoustic spectroscopy. This technique, used by Alexander Graham Bell in 1881 to measure effects of light on solids, has been elegantly adapted by former visiting senior scientist Shmuel Malkin to measure oxygen evolution and energy storage in photosynthesis. Malkin has found that a sample of plant material enclosed in a small air chamber will emit sound when the plant sample is illuminated with intermittent light. The sound itself consists of oscillations in pressure within the chamber brought about both by intermittent oxygen emission and by intermittent heating of the sample, both caused by the intermittent light. By listening to the plant sample with a tiny microphone in the photoacoustic chamber, detecting the oxygen and the thermal components of the emitted sound, one can quantify parts of the photosynthetic process. Since the thermal signal is more rapid than the signal from oxygen evolution, the two are readily measured independently.

Malkin has been collaborating with Fork and postdoctoral fellow Stephen Herbert in using photoacoustic spectroscopy to investigate how the marine alga *Porphyra perforata* (found on rocks in intertidal zones) copes when the tide is out, the temperature elevated, the relative humidity vanishingly small, and the sunlight brilliant. Under these conditions, the alga becomes highly desiccated, photosynthesis grinds to a halt, and the potential for photodamage is severe. One protective mechanism used by *Porphyra perforata* is to increase conversion of the energy of absorbed photons to heat rather than to the excitation of electrons. The alga makes this

transition as it becomes desiccated under full sunlight when the tide is out. Its deep-water relatives have no such capacity, and sustain severe damage under high-light conditions. Higher plants have a capacity for protective thermal conversion similar to that of the intertidal alga.

Fork and his collaborators have also used photoacoustic spectroscopy to look at another kind of response to environmental stress. Photosystems I and II do not absorb the same wavelengths of light, and yet both are linearly coupled to drive electron transport. Obviously in nature, the spectral quality of the light reaching the alga may change—for example, shading by other algae may virtually eliminate certain wavelengths preferentially absorbed by one or the other of the two photosystems. In red algae such as *Porphyra*, where much of the light energy is harvested by specialized antenna pigment complexes called phycobilisomes, mechanisms exist to divert light energy absorbed by the phycobilisomes to whichever of the two systems is the most deprived, thus maintaining a smooth flow of electrons through both systems and avoiding a dangerous build-up of excited electrons. The photoacoustic technique has permitted quantitative kinetic studies of the redistribution of light energy on changes in the spectral quality of the incident light.

Rapid readjustment of energy partitioning represents one of several dynamic mechanisms that the alga uses to protect its photosynthetic machinery during rapidly changing conditions of environmental stress. Olle Björkman and his associates Wolfgang Bilger and Susan Thayer have been concentrating on a possible mechanism whereby leaves safely dissipate excessive excitation energy as heat, thus avoiding photodamage to the photosynthetic apparatus under stressful conditions. Previously Björkman's group had found that leaves grown under weak light were much more susceptible to photoinhibitory damage than leaves of the identical species grown under bright light. The investigators were able to eliminate the trivial explanation that leaves from the high-light environment simply had a higher photosynthetic capacity. They exposed both kinds of leaves to the same amount of *excessive* light energy (an amount of light over and above that need to saturate photosynthesis in each case), and only the leaves from low-light conditions suffered photoinhibitory damage. Hence the investigators concluded that the photosynthetic systems of the leaves from high-light conditions were intrinsically more resistant to photoinhibitory damage than were those from low light. Presumably the former have a more powerful photoprotective mechanism to dissipate excessive excitation energy as heat.

The group next addressed the possible mechanism for this nondestructive energy dissipation, focusing on a family of chloroplast pigments known as carotenoids. A former fellow of the Department,

Barbara Demmig-Adams, has recently shown that there is a very close correlation between the quenching of chlorophyll fluorescence, a phenomenon used as a direct measure of non-radiative energy dissipation, and the reversible formation of the carotenoid zeaxanthin from violoxanthin (a process known as the xanthophyll cycle). This correlation suggested that zeaxanthin might be involved in the dissipation of excess energy, although the exact mechanism was unclear.

Björkman and his associates set about to test this hypothesis in several ways. First, they reasoned that if zeaxanthin really mediated the safe dissipation of excess light energy, then leaves with a high capacity for such energy dissipation should have a large pool of xanthophyll-cycle components, whereas leaves with a low capacity should have a small pool. Extensive studies with a number of species grown under a wide variety of conditions strongly supported this reasoning. For example, leaves developed in full sunlight consistently had pools of xanthophyll cycle components 3–5 times larger than those of shade leaves of the same species. Moreover, the difference was highly specific: There are in chloroplasts carotenoids that play no role in the xanthophyll cycle, and no appreciable consistent differences in these compounds were found between photoresistant and photosensitive leaves. The correlation between photoresistance and the pool size for xanthophyll-cycle components was very strong.

Björkman and colleagues next reasoned that if zeaxanthin was the mediator of excessive energy dissipation, conversion of existing violoxanthin to zeaxanthin should increase with increased excessive light energy (over and above that which saturated photosynthesis). They found this to be true: No conversion of violoxanthin to zeaxanthin occurred as long as the photosynthetic rate was able to keep up with increased light intensity. But if the system was brought into imbalance, either by increasing light intensity still further or by applying drought stress to curtail the carbon dioxide supply, zeaxanthin formation took place. Furthermore, the percentage of the total xanthophyll-cycle pool present as zeaxanthin was closely related to the amount of excessive light applied. Correlations, naturally, even when extremely strong, do not prove causal relationships, and the group is now seeking direct experimental evidence for involvement of zeaxanthin in excessive energy dissipation.

It should be evident from the above discussion that an extremely important component in higher-plant reaction to stressful conditions must reside with the stomata themselves. These pores, which penetrate the plant epidermis, may open or close in response both to internal and external stimuli, regulating the diffusion of air between the interior of the leaf and the environment, and

hence both carbon dioxide uptake and water loss. J. Timothy Ball, a recent Stanford biology graduate student working with Joseph Berry, has provided a notable advance in our understanding of the "rules" regulating stomatal behavior. He has shown that the stomatal conductance of a leaf could be predicted from a very simple empirical equation,

$$g = A(h_s/c_s)m,$$

where $g$ is the stomatal conductance, $A$ is the photosynthetic rate, $h_s$ is the relative humidity at the leaf surface, $c_s$ is the concentration of carbon dioxide at the leaf surface, and $m$ is a constant that is species-dependent.

Berry and his associates G. James Collatz and Cyril Grivet have incorporated this innovation into a model that simulates the exchange of carbon dioxide, water vapor, and heat by leaves in natural environments. Of particular interest are some studies that consider the hot and extremely dry conditions of Death Valley, California. Some years ago, Olle Björkman and his colleagues showed that a number of plants native to other areas of California failed to thrive in Death Valley despite being provided with ample water. As Death Valley is hardly devoid of plants, the plants native to the region must obviously have some special adaptation for this harsh environment. Some of these adaptations have been described, but it has proven difficult to understand those of a group of plants known as spring annuals—species that carpet the desert with wildflowers following particularly heavy winter rains. These plants do not have any greater tolerance for high temperature than do plants from other warm environments, yet they thrive while plants from the subtropics, such as soybean, are completely unsuccessful in Death Valley.

A key observation made by former graduate student James Ehleringer, Harold Mooney of Stanford University, and Berry was that the spring annuals are capable of very high rates of photosynthesis. Indeed, the rate for one such plant, *Camissonia claviformis*, growing under natural conditions in Death Valley, is one of the highest ever recorded for any plant. What is more, the leaves of this plant are often as much as 5°C cooler than the air around them during the hottest part of the day. High rates of water loss through the stomata (transpiration) obviously cool the leaves, and a large conductance of the stomata appeared to be the physiological basis for the effect. Physiological measurements by Ball, Berry, and colleagues showed that the empirical constant $m$ for *Camissonia* is twice as high as for most other plants.

Collatz and Grivet then carried out a series of simulations to determine changes in leaf temperature, transpiration, net photosynthesis, and stomatal conductance during the course of a typical spring day in Death Valley. Figure 1 (top panel) shows such a sim-

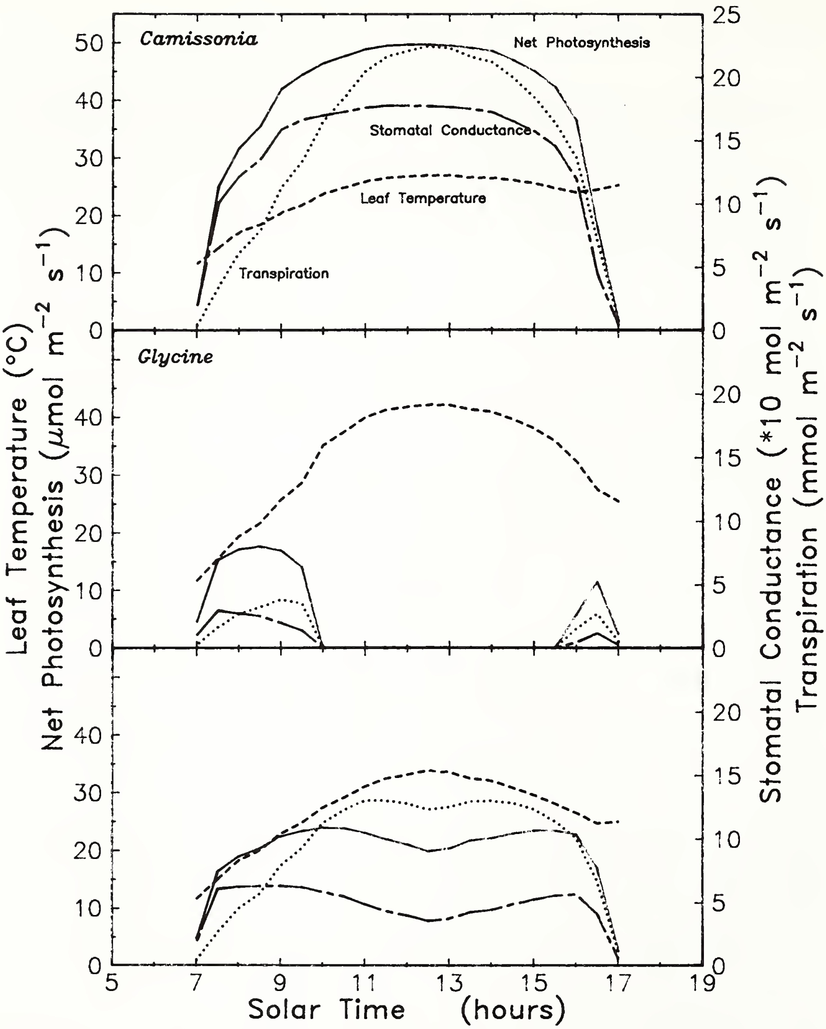



Fig. 1. Simulations of the daily course of net photosynthesis, transpiration of water vapor, and conductance of stomata of leaves with different physiological properties during a typical spring day in Death Valley, California. The top panel shows simulated responses (based on actual physiological measurements) of a Death Valley native, *Camissonia claviformis*. The middle panel shows simulated responses based on physiological properties of soybean (*Glycine max*). The latter simulation predicts that there will be no net photosynthesis or transpiration of soybean during mid-day because the stomata will be tightly closed. The response contrasts sharply with the simulation shown in the bottom panel, which uses the same physiological properties of the soybean leaf, except that the coefficient *m* that describes the response of stomata in the equation developed by Timothy Ball (see text) was changed to match that of *Camissonia*.

The result indicates that it is the difference in stomatal characteristics that allows the desert native to remain productive at high temperature while the soybean, native to more-moist regions, is unsuccessful.

ulation for *Camissonia*. The simulations agreed very well with actual field measurements; maximum leaf temperatures were a good five degrees lower than air temperatures. By contrast, soybean (Fig. 1, center panel) showed a dramatically different pattern. The maximum leaf temperature reached 42°C, near the lethal limit for this species. The difference is in the intrinsic constant $m$. Soybean stomata begin closing at higher relative humidity than do *Camissonia* stomata. If the stomatal characteristics of soybean are changed to resemble those of *Camissonia* (by using the value of $m$ experimentally determined for *Camissonia* without changing any other biochemical parameters of photosynthesis characteristic of soybean), the situation is greatly improved (Fig. 1, bottom panel).

These studies suggest that an intrinsic difference between the responses of the stomata of a desert annual and those of a plant such as soybean is the major factor in permitting the desert plant to remain productive given the extremely low humidity of air in the desert. Studies from other laboratories have shown that differences in sensitivity to low atmospheric humidity between different wheat, barley, and peanut cultivars is heritable. Hence it is of considerable practical importance to determine the physiological bases that determine the value of the empirical constant $m$. Such knowledge would be of great value in selecting crop genotypes for use in hot, arid climates.

Whereas Fork, Björkman, and Berry focus their attention on some component of the individual plant in an effort to understand at the biochemical and biophysical level some of the mechanisms whereby the organism responds to environmental change, Christopher Field looks in the opposite direction. Like the others, he may study physiological processes at the level of the leaf. But his objective is to scale what he learns upward, to the level of the whole plant or, indeed, a complex forest canopy. The underlying assumption is that ecological relationships and ecosystem function can only be understood at the landscape level when they are first understood at the level of driving mechanisms that are species-independent. Field and his colleagues are using this conceptual approach in a number of ways, from analyzing factors determining the habitat breadth of tropical plants, to improving the technology for estimating photosynthesis and plant productivity by remote sensing in space.

Among the various projects in Field's laboratory, controls on the distribution of rain forest plants continues to be a major theme. The black pepper genus *Piper*, whose representative species occupy nearly all types of rain forest habitats, continues to provide the model system for this work. All of the studies in this program aim to integrate carbon income through photosynthesis with the cost of acquiring other resources, such as nitrogen. The Field

group has recently been attempting to quantify the relative roles of light intensity and light spectral quality in regulating aspects of a plant's physiology or developmental pattern and architecture that are potentially important in determining the distribution of a given species.

From a wide range of published studies, one might expect properties of the photosynthetic system, such as photosynthetic capacity or resistance to photoinhibition, to be related to light intensity during growth. On the other hand, one might expect the developmental pattern and final architecture to be determined by light quality, especially by the ratio of red to far red light. Because chlorophyll selectively absorbs red light but not far red light, this ratio is far lower within or under a canopy of leaves than in open sunlight. Furthermore, plants contain an important sensor pigment, phytochrome, which responds precisely and predictably to this ratio, and phytochrome is well known to play an extremely important role in modulating plant development.

Previous studies in the Field laboratory led the group to predict interspecific differences in growth responses and final architecture with variations in light quality. For example, since sun species persist only as long as they remain unshaded, Field and colleagues expected sun species to respond either to low light or to a low red–far red ratio (both indicative of shading by other leaves) by increasing stem growth. By contrast, they expected shade species, which need to minimize the real cost of supporting a photosynthesizing canopy, to respond with decreased stem growth. These predictions were tested with four different species of *Piper* in four different greenhouse environments. Two of these environments had the light spectral quality of open sunlight but differed by a factor of five in intensity. The other two matched these intensities, but had the spectral characteristics of the shaded rain forest understory. In general, the predictions were supported, though responses to differences in light intensity were far stronger than responses to differences in light quality.

These experiments also confirmed the Field group's previous observations that, at least within the genus *Piper*, all species capable of growing within a certain habitat have very similar photosynthetic characteristics in that habitat, whether conditions are optimum for a given species or approach the limits of tolerance for that species. This is not to say that the similarity of photosynthetic characteristics produces similar growth rates. Field's group found that leaf thickness was the most important growth determinant, thin-leaved species producing significantly more leaf area per unit of photosynthesis than thick leaves. While leaf thickness varied with differences in light intensity, in sun species leaf thickness was less sensitive to intensity than in shade species. Light quality did not affect leaf thickness at all, and biomass allocation of the

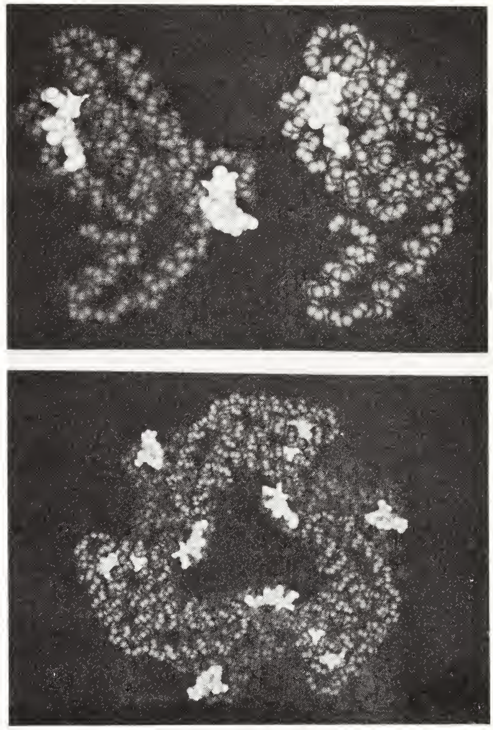
products of photosynthesis to various plant parts showed only limited sensitivity to either light intensity or quality.

Members of Arthur Grossman's laboratory, working with cyanobacteria (blue-green algae), continue to probe how environmental changes induce changes in gene regulation. Many cyanobacteria respond dramatically to changes in light spectral quality, incident light, or nutrient stress with rapid changes in gene expression. Hence they provide a first-rate model system for investigating environmental regulation at the level of the gene. Former fellow Ralf Oelmüller and others in the group have recently shown that when cells of *Fremyella diplosiphon* were moved from red into green light, there was a rapid increase in the rate of transcription of genes coding for the proteins that form a green-light–absorbing photosynthetic pigment, phycoerythrin. When the cells were returned to red light, transcription of these genes gradually decreased. The workers hypothesized that an early consequence of green-light treatment is the production of a specific regulatory protein that binds to the promoter region of the phycoerythrin gene. In the presence of this protein, the gene is transcribed. When the cells are returned to red light, the protein is no longer produced and is gradually diluted out during subsequent growth under red light. As the concentration of this regulatory protein drops, so does the overall rate of transcription of the phycoerythrin genes.

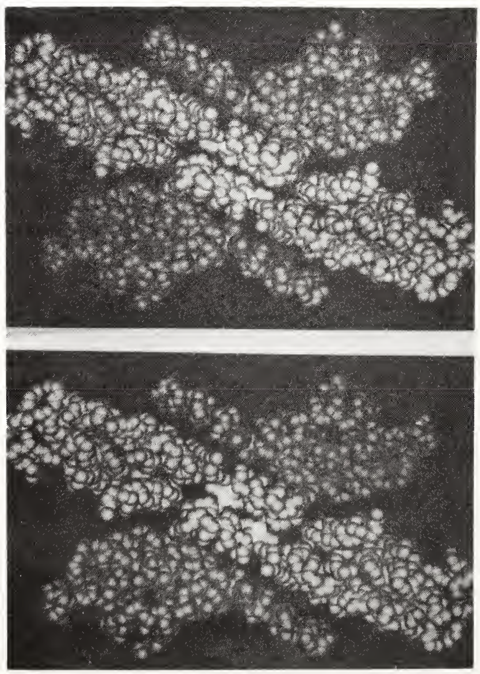
Nancy Federspiel, a postdoctoral fellow working with Grossman, has put this hypothesis to a direct test by using what is known as a gel retardation assay. This technique, in use in many laboratories, consists of placing at one end of a gel a piece of DNA suspected of having a protein-binding site, along with proteins that might bind to it. A voltage imposed on the gel moves the DNA at a rate determined in part by the size of the DNA molecule. If there is a protein associated with the DNA, its rate of movement is slower than that of the naked DNA. Federspiel tested protein extracts from cells grown either under red or green light in the presence of several different sequences of the DNA coding for phycoerythrin, one of which contained the promoter region.

The unambiguous results are shown in Fig. 2. First, retardation is seen only for the DNA fragment containing the promoter region. Second, only protein preparations from cells grown under green light are seen to retard the migration of the promoter fragment.

Though these results support the hypothesis that green light stimulates the production of a specific, DNA-binding regulatory protein, important questions remain to be addressed: How does green light bring about the production of this protein? What are the earlier steps in this transduction chain? Does binding of



Members of the group led by Arthur Grossman are making great progress in investigating the genes and linker proteins involved in the assembly of functional units called phycobilisomes in certain cyanobacteria. Lamont Anderson and Grossman are studying the effects of certain mutations on phycobilisome structure and assembly. The light-harvesting capacity of the biliprotein phycocyanin is a product of covalently attached chromophores, the white atoms shown here in relation to structural models of the peptide backbones of the individual phycocyanin β and α subunits (upper panel) and the $(\alpha\beta)_3$ trimer (lower panel). The phycocyanin genes have been altered to remove the chromophore attachment sites in proteins. (Structure coordinates, courtesy of Dr. R. Huber, Max-Planck Institut für Biochemie.)



Shown here, in another study, a mutation that replaces proline with leucine in the phycocyanin α subunit blocks the assembly of this biliprotein at an intermediate stage. The upper and lower panels are native and mutant protein structures, respectively. The native proline residues are buried in the upper structure; the leucine residues in the mutant are seen as several white atoms near the center of the lower view. (Work of Anderson and Grossman; structure coordinates courtesy of R. Huber.)

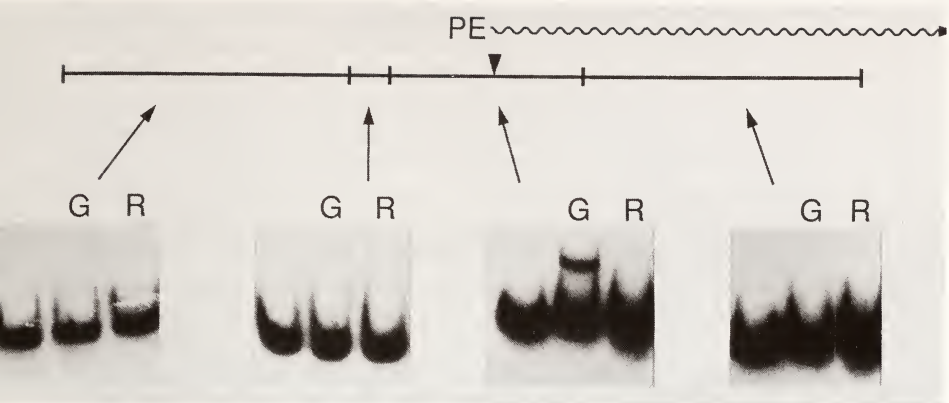



Fig. 2. Gel retardation assay testing for the presence of proteins which may bind to various regions of the phycoerythrin (PE) gene from the cyanobacterium *Fremyella diplosiphon*. The horizontal black line represents the DNA strand, with vertical lines indicating where it was cut to provide discrete pieces for electrophoresis in the absence of protein (left lanes in each panel), in the presence of a protein extract from cells grown in green light (center lanes), or in the presence of a protein extract from cells grown in red light (right lanes). The wavy line represents the location of the PE gene in the DNA; the gene is transcribed from left to right, starting at the arrowhead, and the region immediately to the right of the arrowhead contains the promoter. Note that only the piece of DNA containing the promoter is retarded, and only by a protein in the extract of cells grown under green light. (Direction of DNA movement is from top to bottom.)

These results, by Nancy Federspiel, support the hypothesis that a specific DNA-binding regulatory protein accounts for increased PE production in green light (see text).

this protein genuinely promote transcription of the phycoerythrin gene? These questions are addressable, and *Fremyella diplosiphon* is clearly living up to its reputation as an excellent model system for studying the regulation of gene expression by light.

The Grossman group is also making dramatic progress in elucidating at the molecular level the consequences of nutrient stress in another cyanobacterium, *Anacystis nidulans*. Former graduate student Laura Green had shown that when cells of this organism were starved for sulfur (normally provided as sulfate), their rate of sulfate uptake was enhanced some 10–20 fold during acclimation of the cells to sulfur stress. A number of major new proteins accumulated in the starved cells; at least four of these were membrane-associated and another five were soluble. Green was able to isolate a region of the *Anacystis* genome that contained DNA sequences homologous to those from the bacterium *Salmonella typhimurium* that encode components for sulfate transport in that organism. She could detect transcripts from this region of the

*Anacystis* genome, but only in cells starved for sulfur.

David Laudenbach has now sequenced this entire region and demonstrated that it encodes four components of the sulfate transport system: a sulfate-binding protein, two proteins involved in the formation of a special trans-membrane channel, and an ATP-binding protein. (ATP hydrolysis is required for sulfate transport.) Laudenbach was able to confirm the functions of these gene products genetically, and his sequence data for the channel proteins and the ATP-binding protein represent the first reported for membrane components of sulfate transport in any organism. He has also obtained strong evidence showing that the sulfate-binding protein is directly involved in sensing the sulfate status of the environment.

Near the cluster of genes just mentioned, Laudenbach has found a second cluster of genes, also activated by sulfur limitation. While the precise function of the proteins encoded by these genes is not known, Grossman and Laudenbach have evidence that they, too, are involved in sulfur acquisition. It is clear that *Anacystis* is to nutrient stress what *Fremyella* is to spectral change in incident light: Each is a superb model system for investigating gene regulation by environmental change.

As discussed above, photosynthesis in plants is driven by two coupled light reactions mediated by pigment-protein complexes (Photosystems I and II). Each of these photosystems, located in the chloroplasts, contains a number of unique polypeptides encoded by specific nuclear genes. Neil Hoffman and his associates are investigating properties of these proteins responsible for directing them to their specific locations within the chloroplasts. Consider, for example, a given Photosystem II protein. Synthesized in the cytoplasm of the cell, it must somehow find its way across the chloroplast envelope (two membranes) and across the solution phase of the chloroplast (the stroma), to become inserted in concert with the other Photosystem II polypeptides into a precise location in the thylakoid membranes, where the light reactions and photosynthetically driven electron transport takes place. For a Photosystem I polypeptide, the pathway is the same until the very end, when the protein must find its way to a different location on the thylakoid membrane and associate with other polypeptides associated exclusively with Photosystem I.

Hoffman now has in hand gene clones for eight different polypeptides—five from Photosystem II and three from Photosystem I. These proteins have certain features in common. All have a so-called transit peptide, which is a chain of hydrophobic amino acids situated at one end and involved in moving the protein across the chloroplast membrane and into the stroma, to be cleaved off when transport is complete. All also have three internal sequences of hydrophobic sequences long enough to span the thylakoid

membrane and almost certainly involved in inserting the protein into the thylakoid membrane.

The technique for investigating which regions of a given protein determine its pathway to, and insertion into, its final destination is in principle relatively straightforward. With the complete genes in hand, Hoffman and his colleagues can "cut and paste" the DNA to fuse particular regions of one gene to particular regions of another. They then transcribe the genes to make fusion mRNAs and translate the mRNAs to make fusion proteins. These can be synthesized from radiolabeled precursors and provided to isolated chloroplasts, and their final destinations can be then determined by isolating Photosystem I and II complexes and determining which one is radioactive. The first experiments involved switching transit peptides between Photosystem I and Photosystem II proteins to determine the roles the transit peptides play in determining pathway and destination. The investigators found that there is, in fact, no effect of the transit peptides on the ultimate assembly of the polypeptides. Thus Hoffman and co-workers can state unambiguously that the transit peptides, well known to play a role in protein sorting to and within the chloroplast, have no influence on final assembly. The investigators are now in the process of constructing fusions involving other parts of these protein molecules to try to define the precise regions that target them specifically to Photosystem I or Photosystem II.

Though much remains to be done, Hoffman and colleagues have largely completed the difficult and time-consuming tasks of obtaining clones for the genes, obtaining the sequence information needed to do the cutting and pasting, and developing the system for determining the final destination of the fusion proteins. They are now in a strong position to address head-on questions as to what parts and properties of a given protein lead it to its ultimate address.

The Briggs laboratory continues to pursue its long-standing interest in how light regulates plant development, whether through phytochrome or through photoreceptors that absorb light in the blue and ultraviolet regions of the spectrum. Loverine Taylor has recently completed a detailed study of the light regulation of expression of a family of genes involved in the synthesis of anthocyanins in maize. Anthocyanins are purple pigments found in a number of different cultivars, and a great deal is known about the genes that encode many of the enzymes along the anthocyanin synthesis pathway. Furthermore, thanks to the enormous efforts of the maize genetics community, it is possible to obtain cultivars that are genetically identical at all loci save for one encoding a protein with a specific function in the anthocyanin synthesis pathway. Against the right genetic background, one can readily demonstrate

a light requirement for anthocyanin synthesis and investigate what effect light has on the accumulation of specific pertinent gene products.

In light-sensitive cultivars, Taylor has shown that there are several different patterns of gene expression induced by light. Certain genes are induced to a certain extent by low-intensity red light but require very-high-intensity white light to reach their full expression. Others are not expressed at all under dim red light, and are fully induced only by high-intensity white light. Still others are expressed to a certain extent either in darkness or dim red light, and their expression is merely enhanced by white light. One of the genes of interest encodes not a functional enzyme but rather a regulatory protein of some sort (analogous to the regulatory protein from *Fremyella* being investigated by Nancy Federspiel). Taylor has shown that the level of expression of this gene is under light control; this is the first example in higher plants of a light effect on a regulatory gene. Presumably the protein product of this gene interacts with the promoter regions of other genes to initiate or enhance their transcription. Elucidation of the precise sequence of events between photoexcitation of a photoreceptor and appearance of a regulatory protein remains a formidable challenge, but the first important step—demonstration of a light effect on a regulatory gene—has now been accomplished.

The Briggs group is also continuing to pursue its more recent focus on very early events following photoexcitation of various pigments involved in light regulation of development. There is a large and fairly convincing literature indicating that under some circumstances, phytochrome is associated with cell membranes and exerts its action there. Indeed, a number of workers have detected phytochrome in association with specific membrane fractions. Recently Sean Gallagher (former postdoctoral fellow with Peter Ray of Stanford University), Stanford graduate student Timothy Short, and Briggs, in collaboration with Ray and with Lee Pratt of the University of Georgia, demonstrated a specific association of phytochrome with the plasma membrane isolated from dark-grown pea seedlings. As with so many other reports of phytochrome association with membranes, this study was unable to determine unambiguously whether the phytochrome-membrane association occurred within the living cells and was physiologically meaningful, or whether it was simply a nonspecific consequence of a tiny fraction of the large soluble pool of phytochrome sticking to the plasma membrane during the isolation procedure. Clearly what was needed was some functional assay to determine whether the membrane-associated phytochrome could carry out some biologically meaningful function in the test tube.

William Eisinger, on sabbatical leave from Santa Clara University, provided the initial clue. He showed that whereas the total

concentration of soluble phytochrome declined seven- or eight-fold from the top of the seedling to the bottom, the concentration of membrane-associated phytochrome remained relatively constant. This result made nonspecific association of the phytochrome with the plasma membrane unlikely, since if the attachment of the pigment were nonspecific, one might expect the ratio of bound-to-free phytochrome to remain constant, and this clearly was not the case.

Encouraged by these results, Eisinger looked for a functional assay for the membrane-associated phytochrome. It was known from the literature that cells isolated from oat seedlings would release calcium upon exposure to red light and take up calcium in far red light. While the calcium was being transported across the plasma membrane, there was no way of knowing whether the phytochrome was acting directly on the membrane or at some other location in the cell. Eisinger therefore set about to determine whether red and far red light might have similar effects on isolated and purified plasma-membrane vesicles. He was able to demonstrate direct light effects on the vesicles: red light appeared to drive calcium export, and far red light to drive calcium uptake. Calcium is well known to play a crucial role in the regulation of activity of a wide range of enzymes in both plants and animals, and small changes in calcium concentration can be of major developmental consequence. Hence the phenomenon being investigated by Eisinger may well represent an important early step in a transduction chain initiated by phytochrome photoexcitation. Much remains to be done, but the initial observations may represent an important step forward in our understanding of the possible mechanism of phytochrome action.

—*Winslow R. Briggs*

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[1]To August 5, 1988
[2]From July 1, 1988
[3]From June 1, 1989
[4]From July 1, 1988 to October 15, 1988
[5]From January 4, 1989
[6]From December 1, 1988
[7]To December 15, 1988
[8]To March 30, 1989
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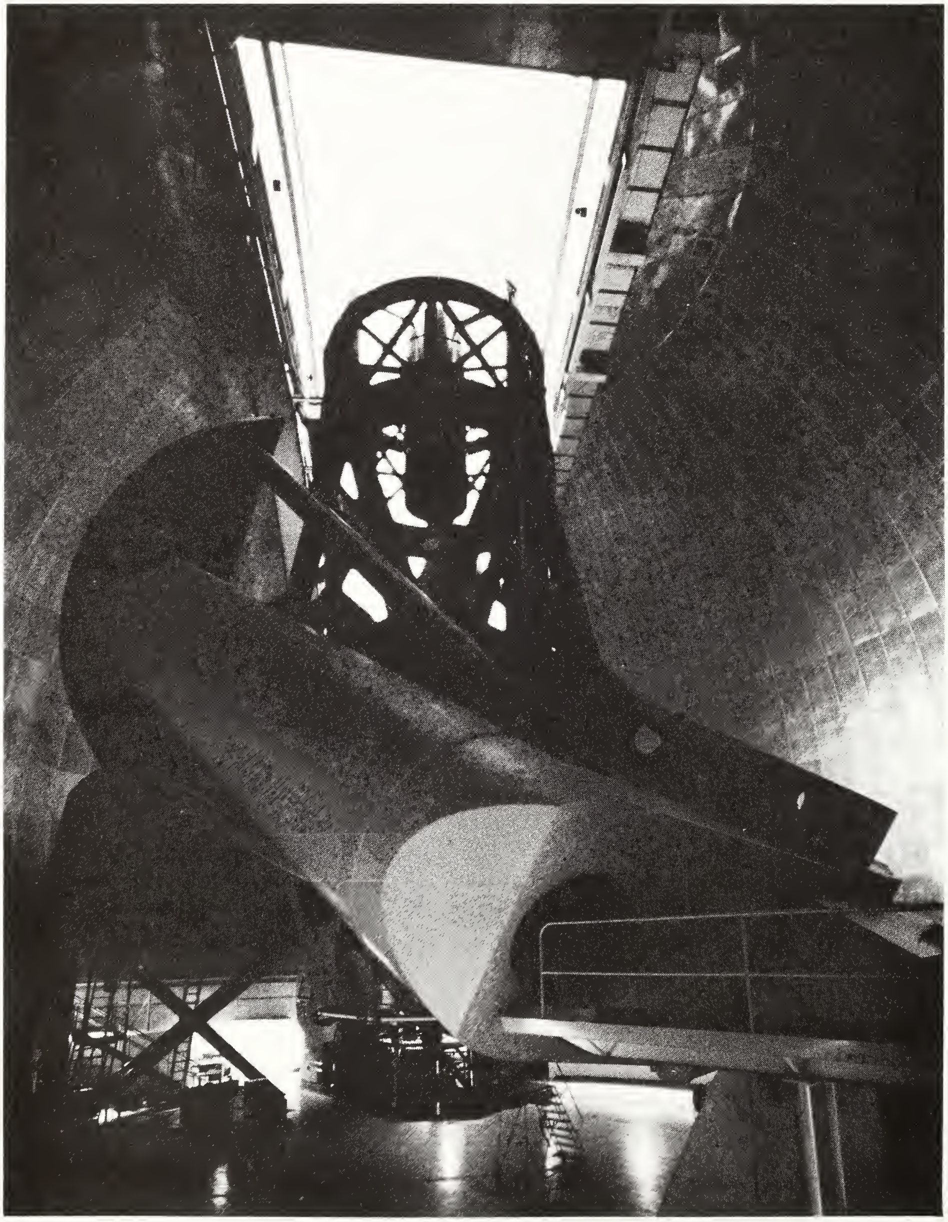
# *The Observatories*



The 5-meter Hale Telescope at Palomar Mountain. (Photo by Jim Pendlay.)

## *The Director's Essay*

The new practice of the Carnegie Observatories is to publish once each year a comprehensive and technical account of the year's work in the *Bulletin of the American Astronomical Society*, where it will appear alongside similar accounts of the year's work of university astronomy departments and other observatories in the United States. In the Year Book, we shall give a more informal and by no means comprehensive, but perhaps equally informative, account of our work.

The Observatories' contribution to this Year Book consists of three essays. In the first of these I intend to isolate one of the research styles that is particularly well supported by the Observatories' facilities and that can be encouraged by careful time-assignment policies. I shall attempt to show how these opportunities have been seized by individuals in a number of very diverse investigations that are currently in progress. In a second essay Alan Dressler summarizes the present state of the Magellan Project. The third essay, by Ian Thompson and Greg Fahlman (University of British Columbia), recounts the context of one particular recent investigation that fully exploits the power of the new generation of detectors, the capacities of the du Pont telescope, and the excellence of the Las Campanas site.

### *Individual Choice and Plentiful Time*

The Observatories of the Carnegie Institution provide a research environment where each scientist has the maximum freedom to pursue work of his or her choosing. In particular, the Observatories maintain a program of postdoctoral fellowships that enables young scientists to have unusual access to major observational facilities and gives them the widest freedom to pursue, with as much independence as they choose, their own lines of inquiry. Their research is supported by the fine suite of telescopes provided by the Institution and diverse modern instrumentation built by the talented scientists and engineers who work at the Observatories' headquarters in Pasadena.

The report year 1988–1989 saw the completion of a redirection of resources intended to phase out operation of some telescopes and to begin on the planning of new facilities. The operation of Mount Wilson Observatory was transferred to the newly established Mount Wilson Institute. The Institute is seeking funding that will enable it to recommission the famous 100-inch Hooker Telescope, which was closed in 1985. The Mount Wilson site remains a fine one for certain specialized areas of astronomical research, but the bright nighttime skies of the Los Angeles region prohibit research there on many of the topics that are central concerns of Carnegie astronomers. In this same year a new agreement was entered into between the Institution and Caltech assuring Carnegie astronomers of 25% of the observing time on the 5-meter Hale Telescope on Palomar Mountain. A similar agreement between Cornell and Caltech makes another 25% of observing time available to the astronomers at Cornell. All main types of optical astronomical investigation are possible with the facilities at Las Campanas and at Palomar, and Carnegie staff members and fellows remain free to choose their research directions without constraints imposed by a deteriorating environment.

The telescopic facilities available to Carnegie astronomers are no longer unique, as they were in the first half of this century, but they are nevertheless remarkable. Most comparable facilities are national facilities, such as the Anglo-Australian Telescope, the Canada-France-Hawaii Telescope, the European Southern Observatory, and the U.S. National Observatories. Excellent science is being done at these observatories, but it is natural that, since they serve large national astronomical communities, the competition for time on the telescopes is severe, and an individual astronomer can hope for only a small ration of nights. In contrast, Carnegie astronomers can be assured of relatively large assignments of telescope time and can be confident of steady support for a project over a period of several years. The styles of science naturally encouraged by these two very different environments are different, and healthy private observatories are complementary to well-funded public ones.

A feature of astronomical research at the Carnegie Observatories that often surprises non-astronomers is that one research project of an individual astronomer may often span several years. In the experimental sciences a good idea is usually followed quickly by a decisive experiment. In astronomical research, in contrast, a good idea can be tested only after some relevant crucial objects have been discovered, and the process of discovery often involves years of painstaking search. Astronomers spend a good deal of time systematically searching for needles in haystacks. Disciplined and well-planned searches are for the observational sciences what the design of experiments is for experimental sciences. In this

aspect of astronomical research, astronomers at the private observatories have opportunities rarely available to their colleagues elsewhere.

In this essay I shall briefly summarize a few pieces of work from this report year that illustrate these themes. I hope to illustrate also the manner in which work with smaller telescopes supports the work of the larger, and why a suite of telescopes of varied aperture is essential to a well-equipped observatory.

*The Preston-Shectman Survey for Very Metal Poor Stars*

Starting in 1980 George Preston and Steve Shectman began a survey for very metal poor stars in the Galactic halo. These stars are thought to be among those first formed in the history of the Galaxy, and their chemical compositions contain information about the earliest nucleosynthesis of the chemical elements in the Galaxy. For three years Preston and Shectman spent two weeks in each year at the Cerro Tololo Observatory in Chile using the Curtis Schmidt telescope, a special photographic survey telescope equipped with an objective prism. In those three years, they obtained plates of eighty fields, each plate taking ninety minutes of exposure. Their observations covered 2000 square degrees of sky. During the next five years, Preston scanned all of these plates and from their objective prism spectra selected a list of many thousand candidate metal-poor stars. As a by-product of the technique used, Preston also identified several thousand Blue Horizontal Branch (BHB) stars, a type of star common in the Galaxy's globular star clusters. This initial phase of the work required uncommon diligence, but nothing extraordinary in the way of telescope time. But the follow-up work required abundant telescope time.

As Preston's lists became available, Shectman conducted a low-resolution spectroscopic campaign with the du Pont Telescope. Observing for about two weeks in each of five years, he confirmed hundreds of Preston's candidates to be extremely metal poor, having iron abundances less than one percent of the solar value. In 1981 Preston began a campaign of photometry, to determine the color and temperature of Shectman's short list. During 1981–1986 he observed about 500 of these metal-poor stars, as well as 1300 of the newly discovered BHB stars, using the Swope Telescope for the brighter stars and the du Pont for the fainter ones. As the work proceeded, catalogs were published and the results made available for analysis by others. Numerous papers and at least one Ph.D. thesis have been based on this search, and many more can confidently be expected. Roughly fifty of the most extremely metal poor stars are now being observed by Preston and Searle, using the high-resolution échelle spectrograph of the du Pont Telescope. This instrument was designed and constructed by Shect-

man, and was brought into commission in 1987. It is hoped that these observations will throw some light on the earliest history of star formation and element synthesis in the Galaxy.

In the meantime, Preston discovered a fascinating phenomenon from the colors of the BHB stars found as a by-product of this investigation. In a suitably defined sample, the average color of the BHB stars in the Galactic halo depends on distance from the Galactic center. The average color of those close to the Galactic center is significantly bluer than is the case for those remote from the center, and there is a steady color gradient over the range from 2 to 12 kpc. This phenomenon is undoubtedly related to the dependence of horizontal-branch morphology on galactocentric distance noted by Searle and Zinn (*Ap. J. 225*, 357, 1978). Preston thinks that age is most likely the "second parameter" needed to explain this phenomenon. If the color gradient is attributed to age, then stars of low metal content first formed rapidly and in profusion near the Galactic center, while those now in the outer halo formed at a more leisurely rate in a different environment. The range in age implied by the range in mean BHB color is a few billion years, according to Preston's analysis.

*An Automated Survey for Quasars*

Ray Weymann and Simon Morris are collaborating with Paul Hewett (Cambridge University), Craig Foltz and Frederick Chaffee (University of Arizona), and Gordon MacAlpine (University of Michigan) in a survey aimed at discovering a large sample (~1000) of QSO's. This survey begins, as did the Preston-Shectman survey, with both direct and objective prism plates obtained with a Schmidt telescope. In this case, the telescope is the UK Schmidt, located at Siding Spring Observatory in Australia. The survey covers seventeen fields and about 600 square degrees of sky. The plates are scanned at Cambridge University, using the Institute of Astronomy's Automated Plate Measuring facility. Among the ~20,000 objects per field in the magnitude range between 16 and 19, approximately eighty are selected by computer algorithms as possible quasars. The great majority of objects on the plates are stars and galaxies, and the computer is taught to reject these and to select only objects which from their color and spectral characteristics have a high probability of being QSO's. As usual, it is the follow-up work that requires large amounts of telescope time.

A spectrum of each candidate is obtained either at the Multiple Mirror Telescope, Arizona, or at the du Pont Telescope at Las Campanas. About two-thirds of the candidates selected in the automatic plate scanning are confirmed by these spectra to be the quasars sought. Weymann and Morris are undertaking follow-up investigations of the sample using both the du Pont and the Hale 5-

meter on Palomar Mountain. The confirmatory spectroscopy is about 90 percent complete, and this "Large Bright Quasar Survey" comprises by far the largest and most homogeneous sample of optically selected QSO's.

The point of a survey such as this is twofold. In the first place many of the questions that arise in interpreting the spectra of quasars require statistical investigations that simply cannot be carried out with small samples. Second, many interesting classes of quasar are rare, so that a large survey is needed to obtain a useful sample of such rarities. One such class of particular interest to Weymann and Morris is that showing broad absorption lines. The numerous narrow absorption lines commonly seen in quasar spectra are thought to be mostly Lyman-alpha absorption lines of neutral hydrogen that arise when the quasar light traverses clouds of intergalactic gas. The rare broad-absorption-line systems appear to arise in circum-quasar matter outflowing from the quasar source itself. Weymann and Morris are using the Hale 5-meter to make a detailed study of the newly discovered broad-absorption-line quasars.

Another class of rare quasars has extremely strong Lyman-alpha absorption lines in their spectra. Such systems are thought to arise when the light from the quasar passes through a gas mass that is the progenitor of a galactic disk. In any case the high column density allows the study of associated weak lines of numerous elements not normally seen in quasar absorption-line systems. These systems allow the study of the chemical composition of the intervening cloud at high redshifts, enhancing understanding of the chemical composition of galactic disks in the remote past. Jill Bechtold (University of Arizona), a former Carnegie Fellow and now Research Associate of the Observatories, together with A. Wolfe (University of California at San Diego) has used the échelle spectrograph of the du Pont Telescope to study two such quasars in the past year. Bechtold collaborated with Shectman in constructing the échelle spectrograph and in writing the data-reduction software, and she continues to collaborate with him in the study of the more common type of narrow-absorption-line quasars. Here the interest is not in the quasars themselves but in the spatial distribution of the intergalactic clouds which give rise to the numerous Lyman-alpha absorption lines, the so-called Lyman-alpha forest.

### *A New Redshift Survey*

As a final example illustrating the use that Carnegie astronomers are making of their substantial and sustained access to excellent facilities, I will cite the new galaxy redshift survey being undertaken by Steve Shectman together with his colleagues Robert Kirshner

Staff astronomers viewing building plans for the future Santa Barbara Street complex: Alan Dressler, Eric Persson, Wendy Freedman, Ian Thompson.

(Harvard), Augustus Oemler (Yale), and Paul Schechter (MIT). In this case a survey of many thousands of objects is being undertaken not to find the few rare objects of interest but rather to sample adequately their distribution in space. It has become clear that galaxies are by no means randomly distributed but perhaps are concentrated in sheets interspersed with voids. The topology remains unclear, and the new survey is intended to investigate such matters on much larger scales than has been attempted heretofore. The galaxies are selected by automated computer analysis of CCD scans of the sky made with the 1-meter Swope Telescope. The total survey will cover an area of ~750 square degrees, distributed in blocks that partially cover a larger area of ~3000 square degrees on the sky. This scanning CCD survey is now 40 percent complete. The enormous follow-up task consists of obtaining spectra of the galaxies selected. For this task, Shectman has made effective use of the wide field of the du Pont Telescope, by employing fiber optics to obtain spectra of many galaxies simultaneously. For the first time at Las Campanas, a full complement of sixty fibers has been implemented for multi-object spectroscopy. The robust mechanical design of these fibers permits practical observations of up to fifty objects in a single exposure, with ten fibers being used to monitor the sky background. The median redshift of the survey

galaxies is 30,000 kilometers per second, the galaxies being many times more remote than those in previous surveys. As of the end of this report year, a total of 460 galaxy redshifts have been obtained. During eight nights in September, 1989, Steve Shectman used the multi-fiber system for the first time in production mode and obtained the redshifts of 1000 galaxies. The survey will take some five years to complete and will involve the redshifts of 10,000 galaxies.

Surveys of the kind I have illustrated constitute only one type of astronomical research. Fellows, who must make an impact with the research they can achieve in three-year fellowships, are not well placed to undertake work of this kind. Neither are those astronomers who must write a new proposal every six months to justify perhaps three nights of access to a telescope. Work like this does not suit all temperaments. It rarely makes the front page of *The New York Times.* It is astronomy for professionals, and astronomers know that whatever style of research they personally prefer, they would not get far without the aid of work of this kind done by earlier generations.

—*Leonard Searle*

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## *Report on the Magellan Project*

**by Alan Dressler***

Once just a gleam in the eye, the 8-meter telescope of the Magellan Project has really begun to take shape. Project Manager Al Hiltner has coupled his experience and skills with those of L&F Industries in Los Angeles to produce a telescope design that is noteworthy for its strength, simplicity, and economy. The 8-m combines qualities of powerful scientific potential with well-established design and construction methods, providing a telescope that requires minimal developments beyond the state-of-the-art in optics, mechanical, and electronic components.

Under the 1986 agreement between Carnegie Institution, the University of Arizona, and The Johns Hopkins University, we are now nearing the end of Phase I, which calls for the demonstration of the technological feasibility and the development of a conceptual design, including a total financial plan. Meanwhile, important steps have been taken toward producing the 8-m mirror, the heart of the telescope. Progress at the University of Arizona's Mirror Lab under the direction of Dr. Roger Angel has been steady and without setback. Two virtually flawless borosilicate (Pyrex) mirrors of 3.5-m diameter have been cast with the fully operational

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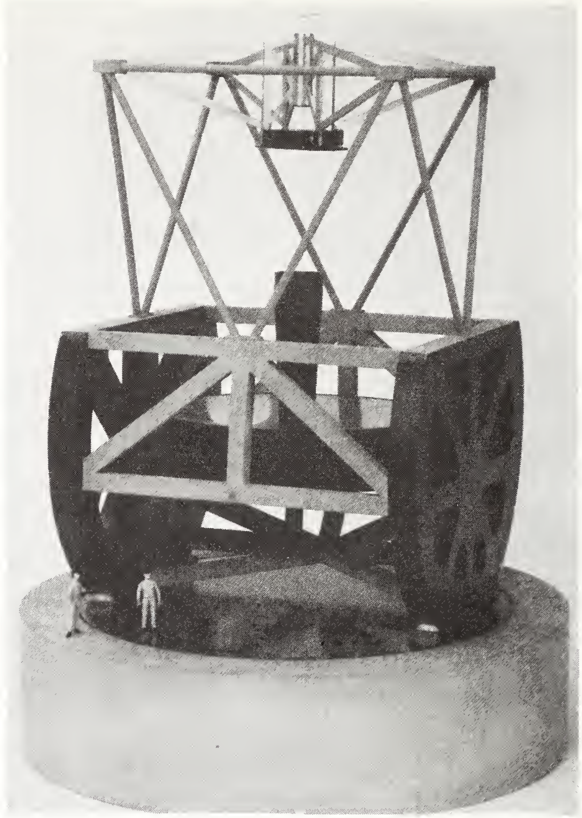
*Associate Director for Magellan



Rough model of the future Magellan 8-meter mirror and mounting.

spinning oven that will be used to produce the 8-m mirror for the Magellan telescope. The honeycomb design means that the mirror weighs only one-quarter that of a solid piece of Pyrex—the mirror is both light and strong. Furthermore, the spinning of the oven produces the approximate curve of the finished mirror, saving what would amount to years of work in "rough grinding" an 8-m mirror.

A third and final 3.5-m casting took place at the end of June 1989. After it has cooled sufficiently to be removed, the interior section of the oven will be modified to accommodate the casting of a 6.5-m mirror in late 1990, and then the first of the 8-m mirrors roughly a year later. The present schedule calls for the casting of the Magellan mirror in late 1992. A "large-optics advisory committee," with representatives of many institutions interested in Angel mirrors, recently commissioned a technical review in connection with its charge of providing supportive feedback to the Mirror Lab. The opinion of the review committee of experts was that the successful casting of 8-m mirrors is now virtually assured.

The Magellan Project relies on more than just a successful casting, however. The 8-m mirror must be polished efficiently and economically to a parabolic figure with a fast focal ratio. The focal ratio of the mirror, i.e., the ratio of the focal distance to the

diameter of the mirror, is a strong driver in the cost of the telescope. Simply put, longer telescopes are more expensive to build and house. The goal of the Magellan, Columbus, and MMT telescope programs (all employing 8-m mirrors) is to produce f/1.2 mirrors, i.e., a focus only 10 meters in front of the mirror. This requires a steep curve, and it is the accurate and swift production of this curve that is the major technical challenge remaining in the Magellan project.

Despite its appearance, glass behaves more like a liquid than a solid. It can be worked by the age-old technique of rubbing two pieces together with some abrasive material in between. The natural action is for microscopic chunks of glass to be loosened from the piece above and redeposited on the piece below. If the two pieces are moved over each other in a fairly random way, the surfaces generated are ever-deepening spheres. This is expected because only spheres can be in perfect contact regardless of how the two pieces are moved—if there is mismatch, it will be ground down. The problem is that a parabola, not a sphere, is needed to focus the light of a distant star. For a mirror with a very shallow curve, the difference between a sphere and a parabola is small, and it can be achieved by varying the strokes to defeat the tendency of the two pieces of glass to stay in perfect contact. As one moves toward deeper and deeper curves, however, the difference between sphere and parabola grows, and it requires an increasing mixture of luck, black art, and time to work against nature's desire to produce a sphere.

Roger Angel's ingenious solution has been to design a computer-controlled polisher to deform the working tool, called the lap, to the desired parabolic shape. By continually deforming the tool as it passes over the mirror, one is again achieving perfect contact, but this time for a parabola instead of a sphere. If successful, this procedure will revolutionize the production of large telescope mirrors, making it as easy to produce a parabola or other figure as it has been to make spheres—i.e., very easy.

This technique is being implemented in the polishing of a 1.8-m mirror for the Vatican telescope, which will have a focal ratio of f/1! This will be the largest mirror ever polished to such a deep parabola, and will be an important test of the method. A major step in developing this technology has been in learning how to polish with a tool only one-third the diameter of the mirror, since we want the stressed lap to be much smaller than 8-m. This step has already been accomplished, as the computer-controlled polisher at the Mirror Lab has successfully produced a sphere in the 1.8-m using a much smaller tool. In the opinion of the panel of experts, this may have been the crucial step, along with deforming the tool through stressing, a simpler task. First results with the full stressed lap are expected in early 1990, and a finished mirror by the end

of the year. Clearing this major hurdle will go most of the way toward demonstrating the technical feasibility of producing 8-m f/1.2 mirrors. The projected delivery date of a finished Magellan mirror is mid-1994.

The design goal of the mechanical structure of the telescope is to achieve the lowest moving weight with an extremely stiff structure that will not shake or vibrate in response to wind and its own drive system. A major advance allowing us to achieve an excellent design has been the use of computer programs which perform what is called "finite element analysis" on the structural design. These simulations allow Steve Gunnels, the mechanical engineer we are working with in conjunction with L&F Industries, to predict the performance of a very complicated structure with high accuracy. Thus, a minimal structure can be fashioned which achieves the greatest strength for the lowest weight and least complexity. In the past, without such tools, engineers were often forced to overbuild complex structures like bridges, towers, or airplanes, to make sure that they would achieve the necessary stiffness. Of course, most of the added steel went into supporting itself, with the result that such overbuilt structures were quite inefficient—wasteful of materials and labor. The new computer design capabilities have revolutionized this procedure, and the results are apparent in all types of construction, not just in telescope design.

The Magellan telescope and mounting combination has been developed over two years of iterations, and it is among the lightest and strongest ever designed. Its moving weight is only 190 tons, only about one-tenth what a version of the Palomar 5-m Hale Telescope would weigh if scaled to this size. Its lowest resonant frequency—a measurement of the stiffness of the structure—is about 7 cycles per second. This is the frequency at which the telescope would ring if hit by a huge hammer. By comparison, most present telescopes, even though they are much smaller and should be much stiffer, have resonant frequencies of about 1 cycle per second. The difference between 1 and 7 cycles per second is like comparing a pillow and a plank, since the wind has a lot of gustiness at the 1 cycle per second level but very little at 7 cycles per second. This stiffness has been achieved by replacing the traditional fork mount, which has large "bending moments," with a design that suspends the telescope between two large wheels, which directly channel stresses in the structure to a firmly grounded, rotating platform. Thus the telescope will resist flexure and oscillation and won't wander around the starfield as wind and drive perturbations come and go. This is essential for exploiting the excellent image quality obtainable at Las Campanas.

Significant progress is now being made in such matters as supporting and controlling the secondary mirror, introducing the

ability to rapidly change observing instruments, and developing a vacuum tank capable of depositing a microscopic layer of aluminum on the 8-m mirror. Al Hiltner has looked into dozens of matters to make sure that there are no "show stoppers"—developments whose technology is beyond the state-of-the-art. It appears that there are none, with the possible exception of the production of the secondary mirror. However, success in polishing the 8-m primary mirror will virtually guarantee the ability to polish the secondary mirror, so we must either succeed or fail at both.

Our goal in the design of the telescope enclosure is to produce a strong, well-insulated structure to house the telescope, and an adjoining or separate operations building to house astronomers, technicians, and heat-producing machines. Maintaining a thermal environment in equilibrium with the night air is crucial for good seeing, so insulation and air conditioning are musts. Further, we would like to use commercially available panels for construction, both to cut cost and to allow ease of assembly. The octagonal dome that has been adopted is particularly well adapted to these goals, since there are no curves like those of the traditional hemispherical dome. A prefabricated, insulated panel, available in 40-ft lengths, is being considered for the construction of not only the moving dome but also the walls of the 16-sided building below, as well as the operations building. Consulting architect Richard Rose, who designed the splendid lodge at Las Campanas, has carried these geometrical shapes throughout, resulting in what we think is a bold and striking design unlike any built before.

A major problem is provision for the removal and recoating of the mirror. Al Hiltner's proposed solution is to lower the mirror on a hydraulic cart and run it on rails to the coating facility, probably in a building far enough away that it will not disturb the thermal and atmospheric environment of the telescope enclosure.

The 1986 agreement called for the telescope and facility to be built at a cost of 25–30 million dollars, not including the mirror, which is to be supplied by Arizona. Today the design is much better specified, and contractors like L&F Industries (a firm much respected in the astronomical community for the telescopes they have built, including the du Pont 2.5-m at Las Campanas) are providing us with tighter cost estimates. Allowing for inflation since 1986 and even for 10% contingencies in each system, the initial figures are confirmed. It is worth pointing out that the Keck Telescope, widely rumored to be significantly over budget, has come in on target in all its subsystems with the exception of the primary mirror, which employs a revolutionary multi-segment approach entailing off-axis parabolas clearly beyond the state-of-the-art when the Keck project began. We are encouraged that in all other areas—the ones applicable to Magellan—Keck's original cost estimates have been found to be reliable.

No discussion of the Magellan project would be complete without at least a few words about one of the most valuable assets of the Carnegie Institution, the Las Campanas Observatory. Auspiciously, the weather in the last year and a half has been even better than usual: Over 90% of the nights have been successfully worked. Eric Persson has been conducting a survey of the wind, thermal, and seeing conditions around several sites at Las Campanas, and it appears that any of them would be an excellent location for the 8-m telescope. Las Campanas is a truly remarkable place for doing astronomy, and those in the Institution who have devoted so much time, effort, and money deserve enormous credit and thanks for providing an extraordinary research facility, one which will allow Carnegie astronomers for many years to fulfill Andrew Carnegie's best ambitions for the Institution.

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## *The Stellar Population in Globular Clusters*

**by Greg Fahlman* and Ian Thompson**

The globular clusters of our Galaxy are surely among the most majestic objects in the night sky (see Fig. 1). These vast piles, each containing a million or more stars, define the outer structure of the Milky Way and have long played a dominant role in the development of modern astronomy. While stars in any one cluster seem to have the same chemical composition, as a population globular clusters exhibit a range of metallicity roughly from somewhat less than 1% to about 100% of the solar value. This property, together with their spatial distribution and kinematics, suggests that they are survivors from the remote epoch when our Galaxy formed. The current best estimates for individual clusters suggest a common age of about 15 billion years. (The age of a star cluster is estimated by comparing the mass of the brightest stars still producing energy from the fusion of hydrogen in their cores to the predictions of the theory of stellar evolution.)

The past five years or so have seen a remarkably intense effort to exploit the advances in imaging detectors—for example, Charge Coupled Devices (CCD's)—by observing the faint stars in many globular clusters. Much of this work has been aimed at improving the age estimates, but while the photometric data are unquestionably better, the issue of setting absolute ages seems to

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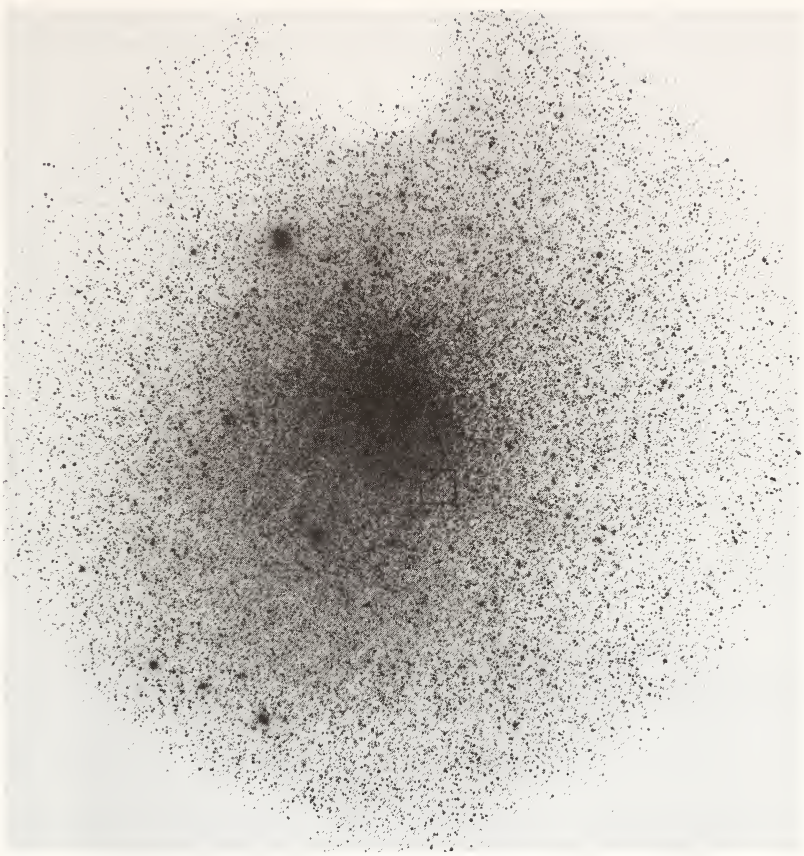

Fig. 1. The globular cluster NGC 6397 (north is up and east is to the left). The total field of view is about 55 arcmin. (The Moon has an apparent diameter of about 30 arcmin on the sky.) The large number of noncluster foreground and background stars is clear; care must be taken in the reductions to properly correct the star counts for this "contamination." The small square to the southwest of the cluster center is 2 arcmin on a side and outlines the field of the CCD observations obtained with the du Pont Telescope.

be as controversial as ever. However the CCD studies can also be applied to another question, a heretofore largely neglected detail: What is the stellar content of a globular cluster?

To astronomers, the answer to this question is the luminosity function, i.e., the distribution of the number of stars in the cluster per unit luminosity. It is obtained by simply counting the total number of stars in a series of brightness intervals in an image of the globular cluster. The theory of stellar structure and evolution provides a relationship between the luminosity of a star and its mass, and with this relationship the luminosity function can be converted into the stellar mass function—i.e., the distribution of

the number of stars in the cluster per unit mass. The mass function is of considerable astrophysical importance because it is manifestly an output of the mysterious processes by which stars form. Prior to the widespread use of CCD's, almost no work had been done on the mass functions of globular clusters.

The typical CCD image of a globular cluster field (Fig. 2) may contain several thousand stellar images spanning a brightness range of a thousand or more. The luminosity function is determined by counting the stars with specialized computer programs, and while this is simple in principle there are certain practical challenges, as may be apparent simply by inspecting Figures 1 and 2. One obvious problem is field contamination. Depending on the location of the cluster and its direction from us, foreground and background stars will be accidentally superimposed on the cluster field. In general, the contaminant stars cannot be directly identified. The star counts must be corrected statistically by subtracting the counts from an appropriately chosen "background" image. (In effect, this doubles the telescope time needed to complete a study to some given limiting magnitude.) At faint magnitudes, the most important contaminant is background galaxies.

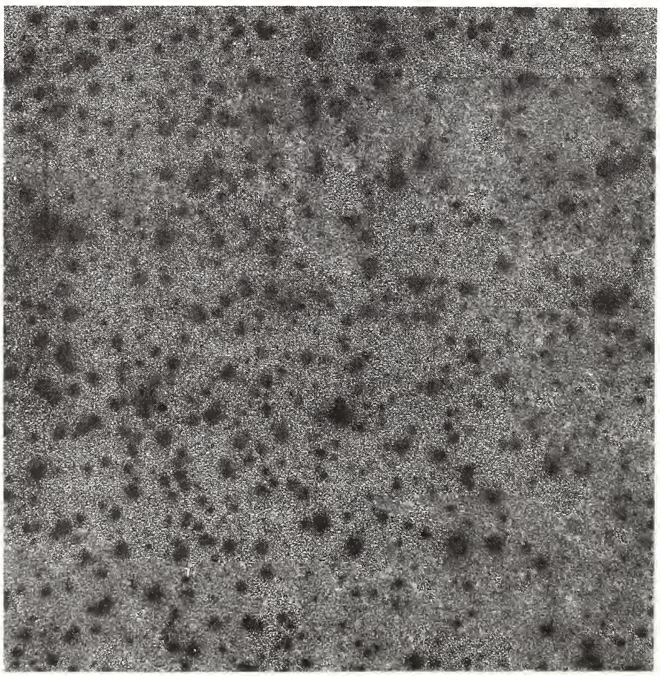

Fig. 2. The CCD observations of NGC 6397. A total of 12 individual exposures of 450 seconds each were co-added to produce this final image. The faintest stars visible have an I-band magnitude of 24.5 and a mass of about 0.12 solar masses.

A second problem concerns the effects of crowding. The Earth's atmosphere distributes the photons from a star over a finite area called the seeing disk. Thus, intrinsically bright stars cover a larger physical area of the CCD image than faint stars. Given the inherently crowded stellar fields of globular clusters, many of the faint stars will be lost behind the glare of their brighter companions. This phenomenon can significantly distort the apparent luminosity function and so requires correction. Incompleteness corrections can be determined empirically by adding scaled replicas of the seeing disk to the observed image at random locations, and re-counting the stars in this modified image of the cluster. The ratio of stars recovered to stars added in a given brightness interval provides estimates of the necessary incompleteness factors. This procedure is computationally very intensive, increasing the data reduction time by about a factor of ten. Clearly, the smaller the seeing disk, the smaller are the completeness corrections. This puts a very high premium on sites with excellent seeing, such as Las Campanas, for this kind of work.

The results to date have been rather unexpected and hence very interesting. The luminosity functions of the main sequence (stars which are powered by hydrogen fusion) differ from cluster to cluster. In 1986, the data from nine clusters was assembled by a group headed by Robert McClure of the Dominion Astrophysical Observatory. A comparison of the luminosity functions suggested a remarkable correlation: the most-metal-poor clusters (poor in elements heavier than hydrogen) had mass functions which increased dramatically toward smaller masses, whereas the more-metal-rich clusters had mass functions which were essentially flat. In other words, the proportion of the total mass in the form of low-mass stars apparently increases as the metallicity of the system decreases. Depending on how far one is willing to extrapolate this result, it could have profound implications for the "dark matter" in the low-metallicity halos of the Milky Way and other galaxies. There are, however, good reasons to be circumspect about the result. Apart from the usual concerns about the small sample size (which is being enlarged) and limited field coverage within a given cluster, there are other, more fundamental issues.

The first concerns the range of stellar masses sampled. Most of the available data have been obtained at visual wavelengths and extend to a typical visual magnitude of $V = 25$. This is sufficient to reach stars which are about a factor of two less massive than the most-massive stars in the cluster; typically the range sampled extends from 0.8 to 0.4 solar masses. In theory, the hydrogen-burning main sequence extends down to about 0.1 solar mass, and it is not at all obvious that the trend seen in the brightest stars continues unaltered to the faintest (lowest-mass) stars. One has good reason to be suspicious because the observed correlation certainly

implies that the total mass–to-light ratios of the metal-poor globular clusters ought to be substantially larger than that of the metal-rich clusters, but this effect is not observed.

The second issue concerns the dynamical structure of the clusters. They are subject to a phenomenon termed "dynamical relaxation," where the stars exchange energy through their mutual gravitational interactions. One consequence of relaxation is segregation by mass within a cluster. The more-massive stars will be concentrated toward the cluster center, and the least-massive stars will extend to greater distances. Therefore the observed luminosity function will exhibit a radial dependence—fields closer to the center will have proportionately more of the brighter and massive stars than fields obtained farther from the center. Simple cluster models which assume complete relaxation can be used to estimate corrections for this effect. The observed metallicity correlation is reduced—the difference between the most-metal-rich and most-metal-poor clusters is smaller—but nevertheless remains significant. Unfortunately, real clusters are not in such a state of equilibrium, and therefore applicability of the simple models is questionable.

From the above discussion, it is clear that the interpretation of an observed visual-band luminosity function involves some difficult points. It is possible to avoid some of the problems by tailoring the observing program to address the issues more directly. For example, by obtaining data in two or more fields distributed radially in a cluster, the amount of mass segregation can be estimated. Similarly, by observing in the near-infrared instead of the visual band, the faint cool stars are easier to find and count. Finally, the closest clusters should be observed preferentially, since they will be the first to yield whatever secrets might be hidden at the faintest luminosity.

The nearest globular cluster is NGC 6397, a fairly typical example, illustrated in Figures 1 and 2. Its distance can be inferred from the apparent brightness of its RR Lyrae stars and is about 3 Kpc. It was our primary target in a weather-shortened observing run on the du Pont Telescope in May 1988 and in a very successful run at the end of May 1989. Our strategy in the first run was to obtain the deepest possible data in a carefully chosen cluster field by observing in the I band near 850 nm. In 1989, we were able to accumulate data in additional radial fields and extend the observations of the background fields. This is an expensive program in telescope time when compared to typical studies carried out for age determination, but it promises to yield results which recently were thought to be obtainable only with the Hubble Space Telescope.

The luminosity function from the May 1988 observations has been converted to the mass function illustrated in Figure 3. There are two interesting points to note. (1) The mass function is relatively

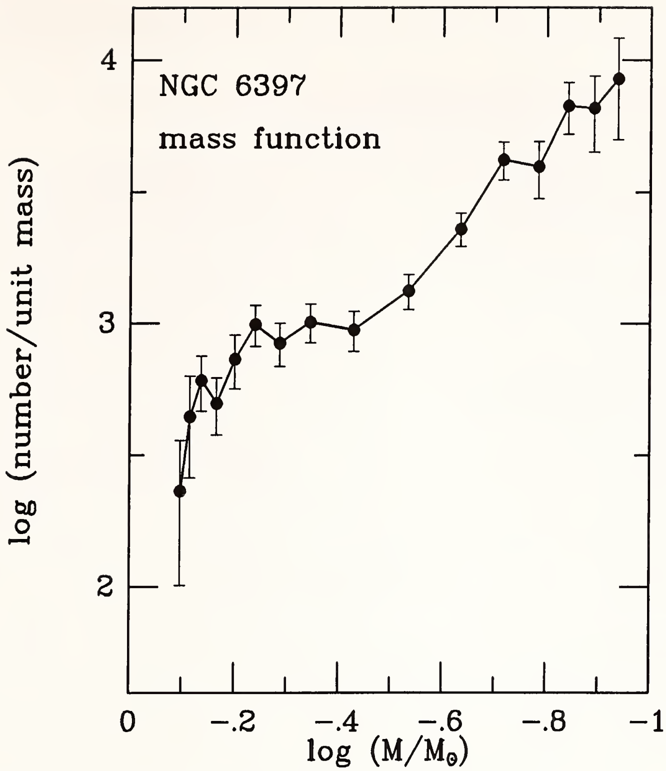


Fig. 3. The mass function for main sequence stars in NGC 6397. Stars are counted in bins according to mass. The most-massive are plotted toward the left–i.e., log ($M/M_{\odot}$) of zero equals 1 solar mass, and log ($M/M_{\odot}$) of −1 equals 0.1 solar masses. Vertical scale, log (number/unit mass), represents star counts in bins of equivalent size.

Note that the number of stars in this logarithmic plot is still increasing sharply down to the limit of the present data at 0.12 solar masses, suggesting that this cluster has a large number of brown dwarfs.

flat on the high-mass side (left side of Fig. 3, which is plotted logarithmically). Since NGC 6397 is quite metal poor, this result is at odds with the mass-metallicity correlation described above. At about a mass of 0.4 solar masses, or log ($M/M_{\odot}$) of about −.4, a value close to the limit of most data now available for other clusters, the mass function begins to increase as the mass decreases. Note that this low-mass behavior could not have been predicted from the observations of the higher-mass stars, reinforcing the fact that it is dangerous to extrapolate the results from sampling a small segment of the cluster mass function. (2) The lowest-mass point (upper right of Fig. 3) is for a bin whose lower boundary at 0.11 solar masses is coincident with the most current estimate of the lowest-mass object capable of sustaining core nuclear fusion. In

other words, Figure 3 shows essentially the complete stellar mass function for the chosen field in NGC 6397.

Evidently the mass function is still rising at the hydrogen-burning limit, but does it continue to even lower masses? This is important because if so there may be large numbers of unseen low-mass stars that contribute a large fraction of the total mass of the cluster. Objects that are too small to become nuclear-powered stars and yet too big to be called planets are termed brown dwarfs. Stars (and brown dwarfs) are thought to form through the collapse and fragmentation of interstellar molecular clouds. Theory suggests that fragmentation will halt when the fragment masses are about 0.01 solar mass, and this can plausibly be identified as the lower mass limit for brown dwarfs. (Smaller bodies, i.e., planets, presumably form through accretion in a nebular disk surrounding a protostellar mass).

Direct observation of the cluster brown dwarfs is not feasible at the present time. Without a nuclear furnace to keep them hot, these objects will simply cool; after 15 billion years, they will be very dark indeed. There is no physical reason why brown dwarfs should not exist, and we can be quite confident that the mass function continues into the brown dwarf regime; the real question is how far. If the observed mass function in NGC 6397 extends to 0.01 solar mass, then one-half of the cluster's present total mass is in the form of brown dwarfs. This possibility—that half of the mass of this globular cluster is in unseen dark matter—has profound implications for topics ranging from studies of the structure of globular clusters to determinations of the masses of galaxies. Confirmation of a significant brown dwarf component in NGC 6397 may be possible through a detailed study of the cluster structure and dynamics. We shall see over the next year or so whether our new observations are sufficient to confirm the presence of a large population of brown dwarfs in NGC 6397.

What about other clusters? There is only one other globular for which the complete stellar mass function is certainly observable from the ground today. There are perhaps five or six others for which it may be possible to obtain such data, particularly if the image quality delivered by the current generation of telescopes continues to improve. The Hubble Space Telescope is unlikely to make a significant impact on this problem unless much more time than is now scheduled is devoted to the study of globular clusters. The best hope for further progress is the new generation of very large telescopes now being planned. For example, with an 8-m telescope on Las Campanas, it will be possible to study some thirty clusters to about the same level of detail as our current study of NGC 6397. This larger sample will allow us to study the mass function over a range of metallicities and ages of the Galactic globular cluster system, and to understand the history of star formation in these clusters. This prospect is eagerly awaited.

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[8]To January 20, 1989
[9]To July 6, 1988
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Shown left to right are Nelson McWhorter, DTM Instrument Maker, Rick Williams, collaborator from the University of Tennessee, Knoxville, Kristján Ágústsson, of the Icelandic Meteorological Office, and Glenn Poe, DTM Electronic Specialist, installing a strainmeter in October 1989 to measure ongoing tectonic activity in Iceland. The DTM team, including Mike Seemann, spent a month in the field. Shown in the background is a modern church built on the site of a famous 16th Century sacred shrine, Skálholt.

## *The Director's Essay*

> Turning and turning in the widening gyre,
> The falcon cannot hear the falconer;
> Things fall apart, the center cannot hold,
> Mere anarchy is loosed upon the world, . . .

Not always, Mr. Yeats. I find most things are more like gravy; they seem to want to become lumpy. As the universe expanded and cooled, much of the homogeneous matter formed in the primordial Big Bang clumped together to form galaxies. Later, this coagulation continued further, to form molecular clouds within galaxies, prestellar disks within molecular clouds, and stars and planets within prestellar disks. Several of us at DTM are trying to understand why and how several of these accumulation processes operate. We study the formation of lumps in the universe not "because it's an interesting little problem," or "because it's there," nor in hope of a spin-off that will lead to better gravy, but because it is a scientific process of far-reaching significance. Without the universal tendency of matter to coagulate, there wouldn't be much science to do at all, even if we were able to do it.

In this essay I will tell about work carried out at DTM during the past few years on the accumulation of interstellar matter to form stars and planetary systems. One thing that makes this easier is that the physical and chemical processes, and the kinds of matter, involved in the formation of our Sun, Earth, and Moon, were quite ordinary—very different from those associated with the magic mystery land of false vacuums, repulsive gravity, nine-dimensional space, and arcane strings of various kinds that one enters in studying the earliest moments in the history of the universe, a domain that may actually have left its imprint on the present distribution of galaxies. The Sun and planets were formed only 4.5 billion years ago in a middle-aged universe, long after the dwindling of the youthful excesses that accompanied the beginning of the Hubble expansion perhaps ten billion years earlier. Despite the

blessing of this relative simplicity, it has only been in the last decade or two that rapid progress has been made in the quantitative understanding of star and planet formation—a result of increased interest in Earth's spatial environment following the dawn of the Space Age, the advent of wonderful new devices for numerical computation and astronomical observation, and widespread appreciation of the beautiful variety of physical expression that stems from the essential nonlinearity of the natural world.

### *Collapse of the Cores of Dark Molecular Clouds to Form Single and Binary Stars*

The principal star-forming regions in the Galaxy are associated with molecular clouds. These range in diameter from about 25 light years to 500 light years, in mass from $10^2$ to $10^6$ solar masses, and, consequently, in density from $10^2$ to $10^6$ times greater than the average interstellar density of about one hydrogen atom per cubic centimeter. They are called molecular clouds because most of their mass consists of molecular hydrogen $H_2$ rather than atomic hydrogen, found elsewhere in interstellar space.

We know *why* a molecular cloud coagulates to form single, double, and multiple stars. The relatively high density of matter found in these regions causes them to become gravitationally unstable. Consequently, at least in the clouds near the small end of this range, portions of clouds tend to clump into "cores" having masses about that of the Sun. These cores then continue to contract because of their own gravitational attraction. In other words, they collapse under their own weight.

Last year (*Year Book 87*, pp. 132–140), John Graham described his observations of these dark molecular cloud cores, and the evidence that new stars are forming, embedded within obscuring shells of dust, deep inside the clouds. We still are trying to understand *how* contraction of clouds and cores takes place, what determines the rate at which cores are formed and collapse, how the temperature, density, and pressure change during the collapse, what determines the final outcome of the collapse (single stars or binary stars), and whether planetary systems are associated with these stars.

We know that the universe didn't coagulate all at once. The process of star formation has operated in a rather restrained way. This restraint is the result of several factors which oppose the tendencies of interstellar clouds to form cores and of the cores to collapse. The first is temperature. It is harder to compress hot gas than cold gas; thermal pressure resists contraction. The second is rotation of the contracting material. As the region contracts to smaller size, it spins more rapidly, and centrifugal force increasingly resists the collapse—a consequence of the law of conservation

of angular (rotational) momentum. The central portion of a rotating cloud can continue to shrink only if some mechanism exists for transfer of angular momentum away from the collapsing region to more distant parts of the cloud.

Finally, there is the effect of magnetic fields. Inasmuch as some of the cloud consists of electrically charged particles, magnetic and associated electrical fields present in the cloud will exert a force on these particles, which in turn are coupled to the much more abundant neutral molecules. In one way, the effect of these magnetic fields is to retard collapse. In a region of space containing a magnetic field, there will be a magnetic energy density, analogous to the thermal energy density of a hot gas, and the associated "magnetic pressure" will resist compression in much the same way as does ordinary thermal gas pressure. In another way, however, the magnetic field helps the cloud to contract, but only if there are enough charged particles in the cloud. The coupling of the charged particles to the magnetic field tends to cause the cloud to rotate as a rigid body, the magnetic field lines acting like spokes on a wheel. As a result, the velocity increases with distance from the rotation axis. This is contrary to the situation when magnetic fields are absent. In that case, when a system of particles simply revolves about its center of gravity, the more distant material will have a lower velocity and a longer period of revolution, as illustrated by the low velocity of the planet Neptune (5 km/sec) in contrast to the Earth's (30 km/sec) and by the corresponding difference in their periods (166 years vs. 1 year). But when magnetic fields cause a portion of the cloud to rotate more like a rigid body, the higher rotation rate of the more distant material can only be achieved at the expense of the rotation rate of the central collapsing region, so as to conserve angular momentum. Angular momentum is transported away from the center of collapse, permitting the central region to contract still further.

The observations by DTM postdoctoral fellow Mark Heyer during his thesis research at the University of Massachusetts permit evaluation of the role played by magnetic fields in the formation of cores and their collapse to form stars. In collaboration with a group of colleagues at the Five College Radio Astronomy Observatory, Heyer found that in dark molecular clouds with gas densities lower than about $10^3$ $H_2$ molecules/$cm^3$, the magnetic field is aligned parallel to the axis of rotation, as expected if magnetic fields are dynamically important (Fig. 1). For this reason, the magnetic processes described probably play a significant role in supporting clouds against collapse. In contrast, in the small, more dense ($>10^4$ $H_2$ molecules/$cm^3$) *cores* within these clouds, the rotational axes are randomly oriented with respect to the magnetic field direction. This suggests that in these core regions, believed to be the sites of low-mass star formation, the coupling between

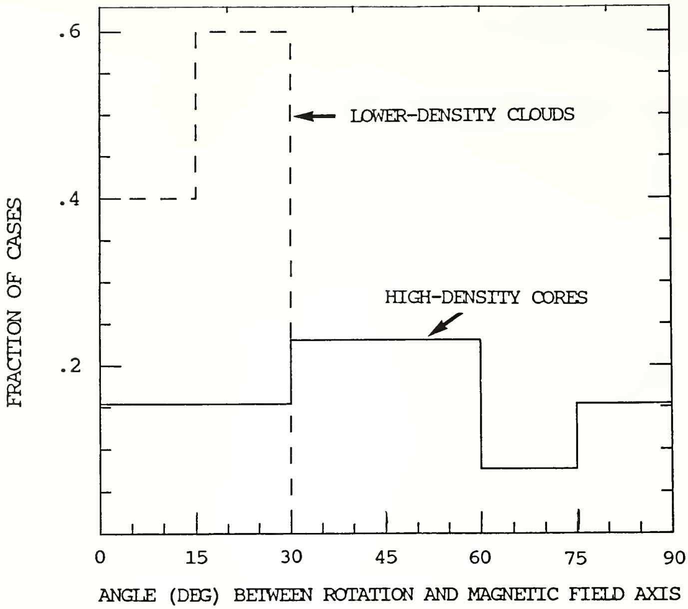



Fig. 1. Observations by Mark Heyer and his co-workers on alignment of rotational and magnetic field axes of dark molecular clouds (dashed histogram) and the denser cores of such clouds (solid histogram). The loss of correlation between these axes as the density increases suggests that magnetic forces do not dominate the dynamics of cores during their collapse to form stars.

charged and neutral particles is much weaker, and magnetic fields are of minor dynamic significance. These observations are in agreement with the theoretical conclusion of T. Mouschovias at the University of Illinois, that magnetic fields may be expected to diffuse out of cloud cores on a time scale of about one million years.

It is possible to derive equations that describe the balance between the forces tending to collapse and those opposing collapse. It is difficult, however, to formulate equations that answer the many other questions one needs to answer: whether the cloud collapses into a single central object or fragments into several objects, whether the collapse of the central region to form a star will leave behind an orbiting disk of material from which planets may form, and if so, what is the mass and temperature distribution in such a disk. Answers to such questions can, however, be obtained by using computers to simulate the collapse process.

Alan Boss has made the first fully three-dimensional calculations of the collapse of a molecular cloud core taking into account the increase in temperature during the collapse. He has numerically calculated the dynamical and thermal evolution of a large number of models of molecular cloud cores having a range of initial masses, radii, rotational velocities, and temperatures. The final sizes and densities found for these models are similar to those of the disks of

gas and dust required at the time of planet formation in our Solar System. Four types of final states are found, illustrated in Figure 2 by three-dimensional computer plots of actual calculations. Figure 2a represents the formation of a binary star, the most common sort observed in our Galaxy. Figure 2d represents the other extreme—a single flattened disk destined to become a single star like the Sun. The other two cases are intermediate: Figure 2b is a "binary bar" where the mass is concentrated toward the end of a bar, while Figure 2c is a "single bar" with the mass concentrated toward its center. Single bars are expected to evolve further to form single stars, whereas binary bars may evolve into either single or double stars.

Earlier work by Boss and others, in which the temperature of the collapsing cloud was assumed to be constant, suggested there may be a problem in forming single stars. If true, this would constitute an embarrassment for theories of the origin of the Solar System, because our Sun is a single star. These earlier calculations were necessarily restricted to rapidly rotating initial clouds, because of the

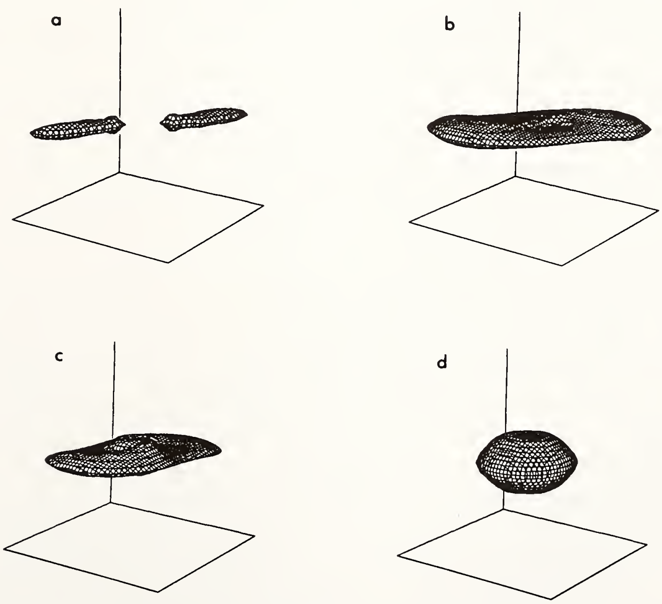



Fig. 2. The four different types of solutions found by Alan Boss in his calculations of the collapse of the core of a molecular cloud. Rapidly rotating clouds or those with low thermal energy relative to their gravitational energy tend to divide into two pieces, usually leading to a binary star (Fig. 2a). At the other extreme (Fig. 2d), a single flattened disk results. In the intermediate cases, evolution into a single star often occurs even when the mass distribution is initially binary.

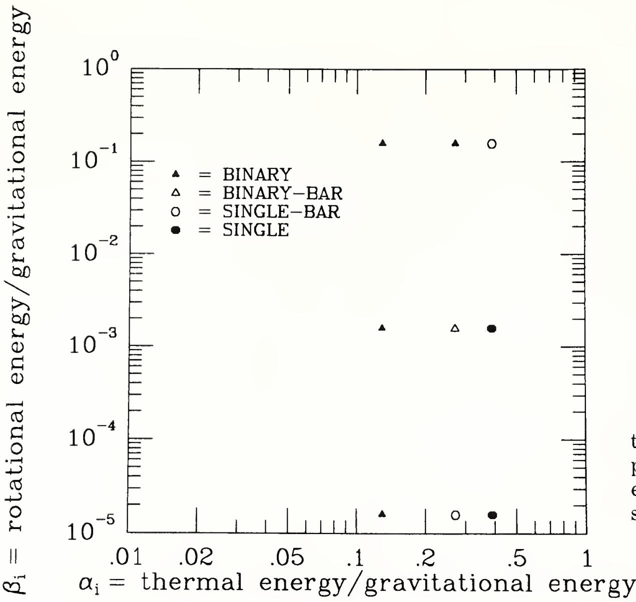



Fig. 3. Results of nine calculations of the collapse of molecular cloud cores. The points represented by solid triangles evolve into binary stars, the remainder into single stars. (See text.)

limited range of validity of the assumption of constant temperature. This rapid rotation tends to form binary, not single stars. When constant temperature is not required, as in Boss's recent models, it turns out that there is no problem.

Among Boss's many models, those with an initial mass similar to the Sun's are of particular interest in earth and planetary science. The results of nine such calculations are shown in Figure 3. The initial mass of 1.03 solar masses is nearly that required to form the Sun and the planets, and the temperature (10K) is typical for cores of dark molecular clouds. The ordinate $\beta$ of the figure is the ratio of the initial rotational energy of the cloud core to its gravitational energy. Large values of $\beta$ correspond to rapidly rotating cores in which centrifugal force tends to produce binary rather than single stars. The abscissa $\alpha$ is the ratio of the thermal energy to the gravitational energy. The value of $\alpha$ must be somewhat less than 1 for collapse to occur at all. Otherwise the thermal pressure of the gas would exceed the self-gravitational attraction of the cloud core and prevent collapse. The smallest values of $\alpha$ favor binary-star formation, higher values favor single-star formation. The reason is somewhat subtle: Low gas pressure associated with low values of thermal energy more readily permits growth of small, three-dimensional fluctuations in density, leading to instabilities that permit binary-star formation.

Two of the nine cases (solid circles) lead directly to a final state consisting of a single flattened disk like that of Figure 2d, the precursor of a single star. In three cases, bars are found (open circles and triangles). Less-rigorous calculations of the subsequent evolution of these objects leads to the prediction that they too will

become single stars. Only the four models corresponding to high values of rotational energy or low values of thermal energy (solid triangles) evolve into binary stars. Although observational data are sparse, the values of $\alpha$ and $\beta$ for which single stars are formed are well within the plausible range of values of these parameters.

In these calculations, Boss made the extreme assumption of uniform initial density. But observed dark cloud cores appear to be centrally concentrated. It is not clear to what extent this concentration is the result of earlier core evolution from a uniform initial state. In calculations made assuming the initial states to be centrally condensed, the density varying inversely with distance from the center, *all* models evolve to single disks. Thus in either case, these three-dimensional, temperature-dependent results eliminate the difficulty of forming single stars of one solar mass.

Another very interesting product is Boss's calculation of the mass of the smallest star that can form by the collapse of a cloud core. This is found to be about one percent the mass of the Sun, well below the minimum value of .08 solar masses required to initiate the thermonuclear reactions responsible for the luminosity of normal stars like the Sun. It has been speculated that the almost invisible stars in this mass range, or brown dwarfs, may contribute significantly to the "missing mass," or dark matter, in the Galaxy. Although they are small, brown dwarfs are still ten times more massive than Jupiter. Thus it does not seem correct to think of our Solar System as a double (or multiple) star system. Jupiter is probably a true planet, like the Earth and other planets, formed by accumulation of smaller bodies rather than by fragmentation of a contracting presolar disk.

### *Evolution of Presolar Disks and the Solar Nebula*

Boss has carried out further calculations toward understanding how a disk, like that of Figure 2d, can evolve into a central star, surrounded by a "solar nebula" of the kind from which planets are believed to form.

The calculations described in the previous section, simulating the contraction of a molecular cloud core to form a single disk, ended after a simulated time of about a million years, at which time the original core size had decreased to about the diameter of our present planetary system. Though the density had increased by a factor of about one million, a central star had not formed, only a single flattened disk (Fig. 2d). If the original core had rotated extremely slowly, it is possible that most of the mass of the original cloud could fall onto the central condensation and form a single star.

For more-realistic higher, but still slow, values of initial rotation rate, in the absence of some mechanism for transferring angular

momentum away from the center of the disk, complete contraction to form a central star would not be possible. The final outcome would be a disk, its further collapse resisted by centrifugal forces, rather than an actual star. Fortunately, there are adequate mechanisms for the transfer of angular momentum. At this stage in star formation, it is probable that the principal mechanism is gravitational coupling between the inner and outer part of the disk. In addition, it is possible that viscosity generated by turbulence in the disk may play an important role in the angular momentum transfer. Recent work suggests, however, that the effect of viscosity has been overestimated in the past. Earlier in this essay, the possibility was discussed that magnetic fields could transport angular momentum away from the center. Angular momentum transport by the coupling of magnetic fields to charged particles was probably an important mechanism in the very initial stages of core formation within dark molecular clouds, but at the relatively high densities of the presolar disks, the level of ionization was probably so low that magnetic fields were of little dynamic significance.

The importance of gravitational transfer of angular momentum was considerably illuminated by the introduction of fully three-dimensional models by Boss. In most earlier disk models it was assumed that the matter was distributed symmetrically about the axis of rotation (axisymmetry). For this reason, these models were unnaturally constrained to be in a sense only two-dimensional. Flow of matter was possible only radially (toward or away from the rotation axis) or parallel to the rotation axis. Azimuthal flow was arbitrarily forbidden.

The manner in which removal of the constraint of axisymmetry permits angular momentum transfer away from the central region can be illustrated qualitatively in a simplistic way. Consider two football-shaped prolate spheroids, one inside the other, with a common axis of rotation (Fig. 4). The inner body is solid, the outer fluid. This arrangement lacks axisymmetry because the footballs are rotating "end-over-end," not "spiralling." Both of the bodies depicted are rotating clockwise. The inner body is rotating slightly faster than the outer body, and is also initially offset slightly in the clockwise direction. Now consider the gravitational influence of the larger body on the smaller one. The deviations of the bodies from sphericity can be qualitatively represented by extra mass concentrations ("mascons") at points $A$ and $A'$ on the larger body and $B$ and $B'$ on the smaller body. The mascon at point $A$ will attract those at both $B$ and $B'$. The attraction along the line $AB$ will tend to cause a counterclockwise rotational force (torque) while that along the line $AB'$ will tend to cause a clockwise rotation. The counterclockwise torque will be greater than the clockwise torque because $A$ is closer to $B$ than it is to $B'$, and gravitational

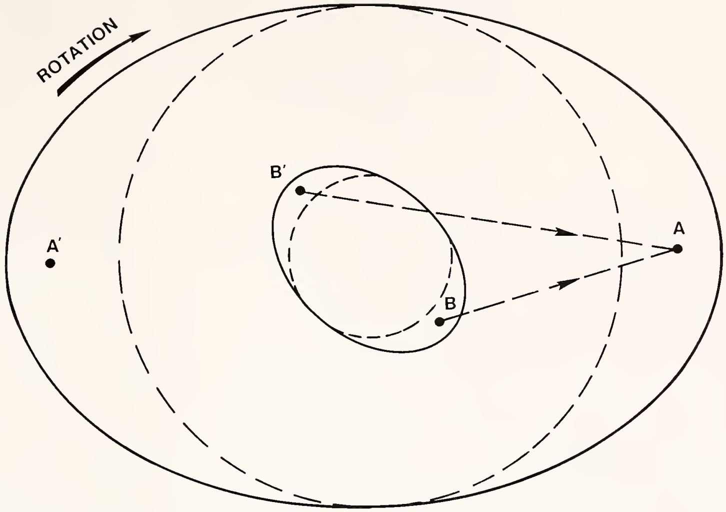


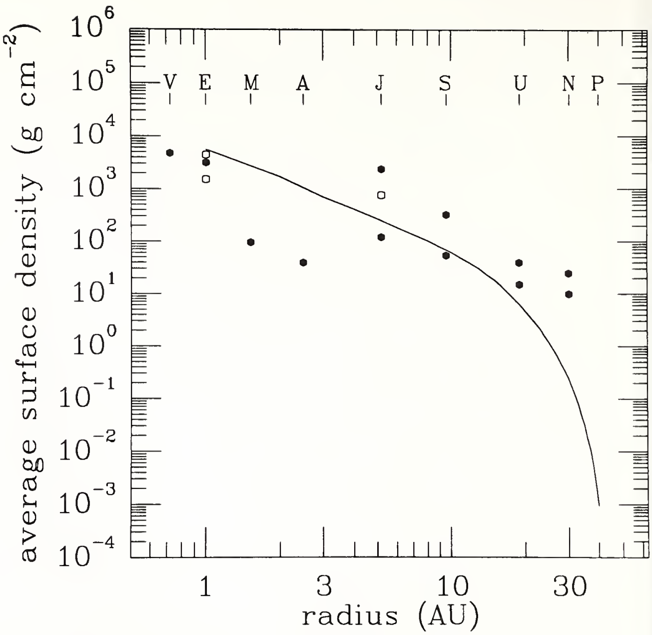

Fig. 4. Simple illustration of how deviation from axisymmetry produces gravitational torques, outward distribution of angular momentum, and collapse of a cloud core. As explained in the text, in a nonaxisymmetric model of this kind, the gravitational attraction between concentric rotating ellipsoids can slow down the rotation of the inner ellipsoid and speed up the outer ellipsoid.

attraction falls off inversely with the square of the distance. In the same way, the forces between point $A'$ and points $B$ and $B'$ will also produce a net counterclockwise torque. The effect will be to slow down the clockwise rotation of the inner ellipsoid. Because angular momentum is conserved, the outer ellipsoid will rotate more rapidly. Angular momentum has been transported outwards. If the inner ellipsoid is undergoing gravitational contraction, its contraction would now be less constrained by its rotation. It is necessary that the angle of offset remain less than 90°; otherwise the angular momentum transfer will be in the opposite direction. It should also be noticed that if either the inner or outer ellipsoid is a sphere, one pair of mascons would disappear, and there would be no net gravitational torque.

In his study of the further evolution of a flattened disk, Boss has carried out a series of 3-D, nonaxisymmetric numerical calculations that model the accumulation of the disk's residual gas and dust onto a central condensation (protostar). Deviation from axisymmetry appears spontaneously as a bar of material in the disk's center. The calculations show that these bars exert strong gravitational torques on the other portions of the disk. Effects of this kind would not be found in models in which deviations from axisymmetry were precluded at the outset.

The results of one of these calculations is shown in Figure 5. The initial system consisted of a sphere having a diameter equal to

Fig. 5a. Calculated density distribution (curved line) in a model residual nebula of 0.05 solar masses surrounding a star of one solar mass, modeled by Alan Boss. The open symbols at the position of Earth (*E*) represent two estimates of the surface density required to form the Earth. The open symbol at the position of Jupiter *J* is J. Lissauer's (S.U.N.Y. Stony Brook) estimate of the surface density required at Jupiter's distance to form Jupiter in about 0.5 million years. The solid symbols are Stuart Weidenschilling's "reconstruction" of the solar nebula, based on the present masses and positions.




that of the present planetary system, containing slightly more than one solar mass and having a central condensation containing only 1% of a solar mass. At the end of the calculation, a central star of 0.99 solar masses formed, and the residual mass of the disk dropped to only 0.05 solar masses, about that necessary to form our planetary system. For practical reasons it was necessary to end the calculation at this time, even though the system had not completed its evolution.

The calculated surface-density distribution at the end of the calculation is shown in Figure 5a. As in the present planetary system, the surface density in the disk (i.e., the mass per unit area as if viewed perpendicularly from above the disk plane) falls off rapidly with distance from the center. The solid circles in this figure represent the smoothed-out mass per unit area of the actual present planets, augmented by the solar composition of volatile elements (primarily hydrogen) that originally accompanied the less volatile constituents of the planets. For the outer planets a range of values is shown, resulting from uncertainties in the chemical compositions of these planets. The open symbols represent two estimates of the surface density required by theoretical models of the formation of the Earth, and the estimate of J. Lissauer (S.U.N.Y. Stony Brook) of that required to form Jupiter in less than a million years.

The principal difference between this calculated mass distribution and that observed in the present Solar System is the gross deficiency of mass between Earth and Jupiter in the actual Solar System. The asteroid belt, occupying much of this region, constitutes a great hole in the mass distribution of the Solar System. Removal of material from this region is usually attributed

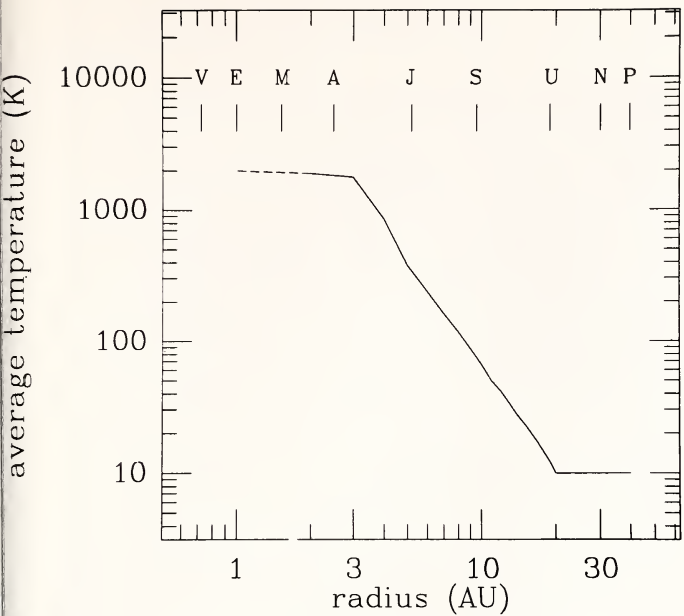



Fig. 5b. Variations of temperature with distance for the model in Fig. 5a. Temperatures in the asteroid belt and the terrestrial regions reach 1500K, high enough to vaporize solid grains of silicate and iron. (The dashed line represents a plausible extrapolation to the terrestrial planet region.)

to the influence of the massive planet Jupiter in preventing, at a later time, the growth of planets nearer to itself. Much of my own current work is directed toward a quantitative understanding of the actual mechanisms by which this was accomplished, and the way in which the material originally present in the asteroid belt and in the neighborhood of Mars was removed from the Solar System.

The variation of temperature with distance in this model of the early solar nebula is shown in Figure 5b. Inside the orbit of Jupiter, the temperatures are found to be high—up to about 1500K in the asteroid belt. These temperatures are much higher than those found in some other recent studies. The difference comes from now including the compressional heating of the gas during its collapse. These temperatures are high enough to volatilize metallic iron as well as the most abundant minerals found in the Earth and in meteorites of asteroidal origin. For a model of this kind, it is expected that a major fraction of the material ultimately found in the Earth, Moon, and meteorites originally condensed from a gaseous state. A significant addition of unvaporized, infalling interstellar particles would also be expected, however, as this nebula evolved further.

*Formation and Growth of Planetesimals*

In order to form planets like Earth, it is necessary that the solid grains condensing from the hot gaseous nebula, together with any unvaporized interstellar grains, first coagulate to form plane-

tesimals, and that the planetesimals then aggregate into planetary embryos and finally planets.

The first stage in this process of planet building involves the sticking together of very small (1/1000 of a millimeter) grains to form particles in the centimeter-sized range large enough to settle down to the central plane of the nebula. It is within this central dust band, probably not much thicker than the diameter of Earth, that planetary growth begins. Stuart Weidenschilling, now at the Planetary Science Institute in Tucson, began his important studies on this early stage of coagulation of nebular dust grains while a postdoctoral fellow at DTM in the late 1970's. Our understanding of how chemical and physical bonding allows these probably fluffy aggregates to grow in the presence of 200-mph headwinds remains incomplete, but Weidenschilling's continuing work indicates there is reason to believe it may not have been too difficult to have formed bodies as large as a few kilometers in diameter within less than 100,000 years. Assuming that bodies of this size formed from dust grains, Glen Stewart, now at the University of Colorado, and I have studied their further growth.

When these bodies reach sizes of about 1–10 km, gravitational interactions between them dominate their further evolution. At the outset the number of planetesimals was very large—about $10^8$ of them are required to form the Earth. It is totally out of the question to follow the changing orbits of so many bodies for $10^5$ orbital periods. One must instead describe a large system of interacting planetesimals by the methods of gas dynamics, the individual planetesimals being the analogs of the gas molecules in the kinetic theory of gases. In this system, two primary processes operate: the planetesimals grow by colliding with one another, and their mutual gravitational perturbations cause their relative velocities to change. During any time interval, the extent of growth and the resulting changes in the size distribution are nonlinear functions of both the existing size distribution and the velocity distribution. The changes in the velocity distribution are also nonlinear functions of the existing velocity distribution and size distribution. Because of this coupled nonlinearity, it is not possible to formulate general equations that represent solutions for the final outcome of this evolution without crippling the calculation with oversimplifying assumptions. Stewart adopted the alternative of deriving new, more-complete mathematical expressions for the changes of size and velocity during a single time interval. We then used these expressions as the basis for a numerical program that calculates how these distributions change with time.

When this was done, we found that for a broad range of hypothesized initial conditions and other assumed parameters, the solutions bifurcate and branch into one of two kinds: orderly growth or runaway growth. The larger bodies of the swarm grow

by colliding with and accumulating the smaller bodies. In the case of orderly growth, a number of larger bodies grow at nearly the same rate, and there is little tendency for one or more to outstrip the others in growth. At the outset, no particular planetesimal should be thought of as the eventual planet Earth or Venus. Rather, as the pioneer investigator of this problem, V.S. Safronov, says, "all planetesimals are created equal." In the orderly-growth solutions, this egalitarianism tends to continue throughout the evolution. There are always a number of bodies at the high end of the mass distribution that are very similar in mass.

Solutions in the runaway branch are quite different. Again, all planetesimals are created equal, but soon one becomes more equal than the others. In all solutions, both orderly and runaway, there will always be a largest body in the swarm if only because of stochastic fluctuations in the number of mergers between colliding bodies. At first, this largest body will be only slightly larger than the second- and third-largest bodies. In the case of orderly growth, the system regulates itself to reduce the rate of growth of the largest body, restoring the equality. In the runaway branch, however, an instability develops that amplifies, rather than retards, the growth rate of the largest body, and it then proceeds to gather to itself all the material within its local region of the planetesimal swarm.

Quite a few parameters affect whether the solution will select the orderly-growth branch or the runaway branch. In our work, however, we found that the principal factor that leads to the runaway branch comes from the inclusion for the first time of new terms in the coupled nonlinear equations describing the evolution of the size and velocity distributions. These expressions, introduced by Stewart in his Ph.D. work at UCLA, and developed further during our collaborative work, are the equivalent of the "equipartition of energy" that appears in gas dynamics, adapted to the more complex case of a system of bodies freely revolving in Keplerian orbits about the Sun.* Because of approximations made in previous work (for example, the pioneering studies of Safronov in Moscow), these terms did not appear. Without these terms, the effect of the mutual gravitational perturbations of the bodies is always to increase the relative velocity. Higher relative velocities favor orderly growth. At high velocities the collisions that lead to growth occur more nearly as simple geometric results of the intersection of their trajectories. At lower approach velocities, however, the stronger

*In an equilibrium gas mixture that contains both light and heavy molecules, the small molecules will move faster than the large, more-sluggish molecules. Nevertheless the kinetic energy of both the large and small molecules are found to be the same; the effect of larger mass exactly offsets that of velocity.

gravitational fields of larger bodies have time to bend the trajectories of the smaller bodies toward the large ones, facilitating the growth of the larger bodies. To some extent, this "gravitational focusing" does occur even when gravitational perturbations are always positive, i.e., where their effect is to increase relative velocity, but for plausible initial conditions the effect is not very great, and orderly growth results.

Figure 6a depicts our calculation of the "Safronov case," in which the mutual gravitational terms are always positive. The spontaneous accumulation of a swarm of approximately 10-km-diameter bodies was calculated. These bodies were assumed to be confined to a narrow zone centered at the Earth's distance from the Sun. (The entire planetesimal swarm consisted of an assemblage of concentric rings of this kind, but during this early stage of growth, the bodies in each individual ring should evolve nearly independently of those in neighboring rings.) The resulting orderly growth leads on a time scale of about a million years to a collection of bodies somewhat smaller than the mass of the Moon. A different outcome is found when the equipartition of energy terms are included (Fig. 6b). For about 50,000 years the evolution of the size distribution is not very different from that shown in Figure 6a. After $1.3 \times 10^5$ years, however, a bulge appears at the high-mass end of this size distribution, signaling the onset of a runaway. During the next $10^5$ years, these bodies agglomerate with one another, leading to a single body that will rapidly accumulate all of the smaller objects in its local zone. After $2.6 \times 10^5$ years, the mass of the large runaway body grows to about that of the present Moon; the second-largest body is much smaller, similar in size to the larger asteroids. The runaway growth will stop when the larger body accumulates all of the material within its "gravitational reach". The size of the runaway body is somewhat uncertain, but at the Earth's distance from the Sun it is in the general range of the masses of the Moon and Mercury. When other effects are included in a calculation of this kind, the time scale for the runaway becomes even shorter, less than $10^5$ years.

Figure 7 shows the relationship between the runaway phenomenon and equipartition of energy. At the beginning, the relative velocities of the planetesimals are expected to be quite low, about 10 meters/second. With the passage of time, their relative velocities will change as a result of their mutual gravitational perturbations. When equipartition of energy is included, the velocity changes are no longer always positive. As seen in Figure 7, after only 32,000 years, the velocities of the larger bodies have decreased below their initial values, whereas the velocities of the smaller bodies have increased considerably. The result is that the effect of the gravitational focusing, mentioned above, will ultimately give the largest bodies an irreversible advantage over

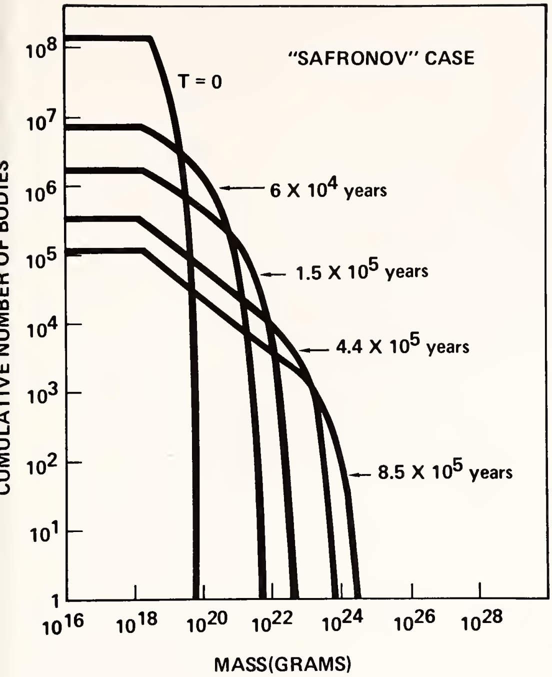



Fig. 6a. Evolution of the mass distribution of a swarm of planetesimals distributed between 0.99 and 1.01 AU for which the velocity distribution is determined entirely by the balance between positive-definite gravitational "pumping up" of velocity and collisional damping. The growth is "orderly"—i.e., it does not lead to a runaway but rather to a mass distribution in which most of the mass is concentrated in $10^{24}$–$10^{25}$-g bodies at the upper end of the distribution.

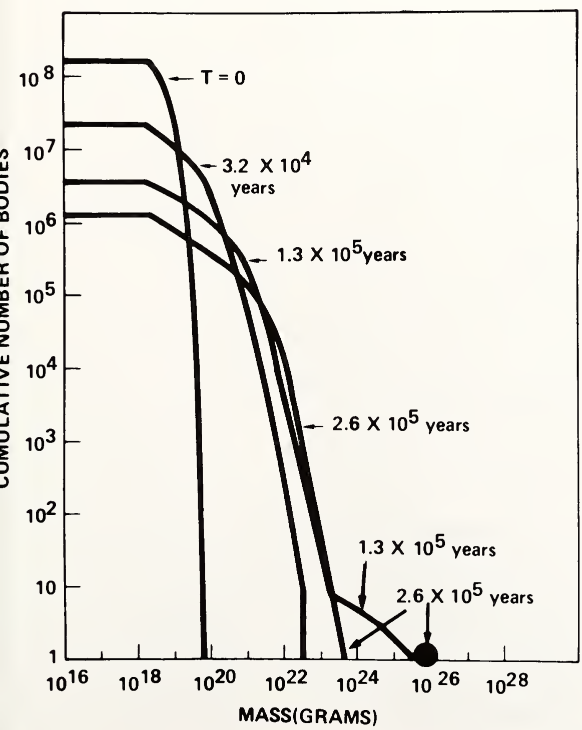



Fig. 6b. Effect on mass distribution of the introduction by George Wetherill and Glen Stewart (University of Colorado) of equipartition of energy terms. The tendency toward equipartition of energy results in a velocity dispersion in which the velocity (with respect to a circular orbit) of the massive bodies falls below that of the swarm. After $1.3 \times 10^5$ years, a "multiple runaway" appears as a bulge in the mass distribution in the mass range $10^{24}$–$10^{25}$ g. After $2.6 \times 10^5$ years, the largest body has swept up these larger bodies, leading to a runaway in which the mass distribution is discontinuous. The single largest body (large solid circle) has a mass of $\sim 10^{26}$ g, whereas the continuous distribution of remaining bodies have masses $< 10^{24}$ g.

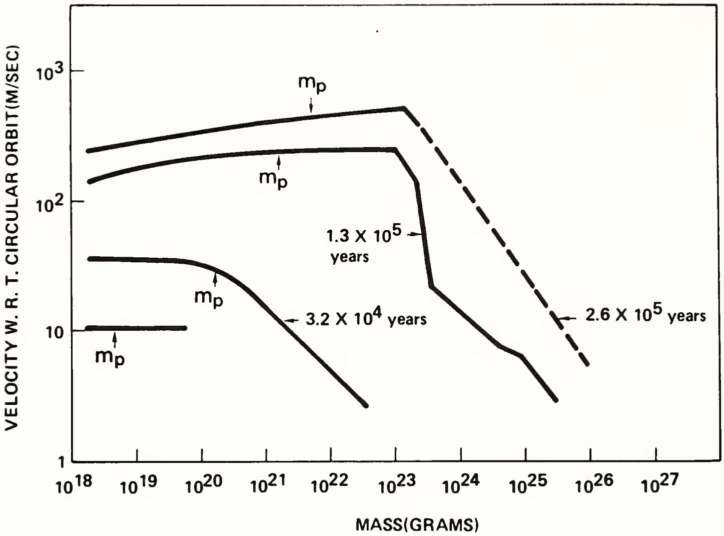



Fig. 7. Velocity distribution of a planetesimal swarm upon inclusion of equipartition of energy terms. After $3 \times 10^4$ years, the relative velocities of the largest bodies (calculated directly from the velocities with respect to circular orbits, as shown in the ordinate of the drawing) drop well below that of the midpoint mass $m_p$. This leads to a rapid growth of the largest bodies, and ultimately to a runaway.

the others, leading to their rapid growth, as shown in Figure 6b, and later, to very low velocity (Fig. 7).

The effect of runaway growth is twofold. It shortens the time scale for growth, and it increases the size of the final bodies. These differences are likely to be of major importance in explaining the growth of the giant planets, Jupiter and Saturn. It seems likely that natural processes that can tip the balance one way or the other between runaway and orderly growth, together with other factors, may solve the long-standing problem of how these planets formed before the gas required for their formation was lost from the solar nebula, and at the same time explain how full-sized planets were prevented from forming in the nearly empty asteroid belt. This possibility is being explored.

## *The Final Stage of Planetary Growth*

In the region of the Earth and the other terrestrial planets, the outcome of the runaway growth of planetesimals discussed in the previous section is found to be the formation of a number of "planetary embryos"—bodies similar in mass to Mercury or the Moon and considerably more numerous than the four present-day terrestrial planets. The final stage of planetary formation, then, consists of the merger of these embryos into final planets.

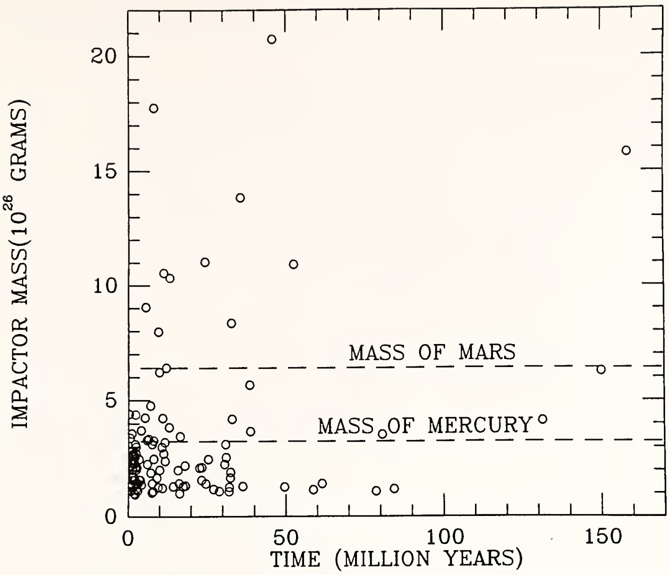



Fig. 8. Size and time of giant impacts on Earth from ten simulations of the final accumulation of runaway embryos, by George Wetherill. On the average, each simulation is associated with one impact on Earth by a body more massive than the present planet Mars and about two impacts by bodies of mass intermediate between those of Mercury and Mars.

Some results of my computer simulations of this final stage of growth were described in *Year Book 84*; these applied to the case of orderly growth. More than a hundred simulations of this general nature have been carried out; most assume the distribution of embryo sizes and orbits resulting from runaway growth during the earlier stage of growth, now known to be more probable. In addition, several other phenomena, such as the effects of collisional fragmentation, tidal interaction of the embryos with residual nebular gas, and resonant perturbations by the giant outer planets have now been studied in an approximate way. As far as the terrestrial planets are concerned, the outcomes of these more-detailed studies are similar to those reported earlier. Because of the highly chaotic nature of orbital evolution dominated by close planetary encounters, the outcomes can be described only in statistical terms. In all cases, a small number (2–5) bodies in the general mass range and position of the present terrestrial planets are found.

These simulations represent the only three-dimensional calculations of the simultaneous accumulation of several planets. They illustrate the probable importance of several phenomena that could not be clearly addressed or recognized in calculations limited to two-dimensions or to accumulation of only one planet. Among these phenomena is the widespread migration of planetary embryos during planet formation. Such migration will tend to smooth out radial variations in chemical composition that may have existed in the

solar nebula as a consequence of variation of temperature and pressure with distance from the Sun. Another of these phenomena are giant impacts—collisions with bodies up to twice the present mass of Mars—which are likely to have occurred on Earth and Venus during their growth. The timing and mass of giant impacts resulting from a recent set of simulations are shown in Figure 8.

Impacts of this magnitude would have profound effects on the early history of the Earth. Perhaps the most interesting of these is the support it gives to an earlier suggestion of A. G. W. Cameron (Harvard-Smithsonian Center for Astrophysics) and W. Hartman and D. Davis (Planetary Science Institute, Tucson), explaining the origin of the Moon by a giant impact on the Earth. Such an impact could have "splashed" vaporized material from the Earth into orbit, where it could have mixed with similar material from the giant impacting projectile, and then condensed and coagulated to form the Moon. A model of this kind may prove to be the only dynamically consistent way to explain the remarkably high angular momentum of the Earth-Moon system.

Further study of these processes is occupying the attention of many scientists, including DTM's Richard Carlson, who has examined the relationship between a possible giant impact and isotopic age studies of lunar rocks returned by the Apollo program of lunar exploration.

*The Initial State and Early History of the Earth*

An obvious consequence of the giant impacts discussed above is that most of the Earth would be heated, on the average, to the melting point or higher. Expectation of a highly melted initial state of the Earth does not actually require the impacts to be as large as those predicted above; accumulation of the Earth from bodies as small as 300 km in diameter would still produce major early melting. The geological record appears, at least at first glance, to contradict this condition. Geological studies of ancient terrestrial rocks show that the Earth's surface had cooled to near its present temperature as early as 3.8 billion years ago. This is demonstrated most clearly by the existence of water-lain sediments in the ancient geologic record, indicative of the presence of substantial bodies of liquid water on the surface, either large lakes or oceans. Many of the crustal rock types present in the ancient continental areas also share petrologic and geochemical characteristics with modern igneous provinces, indicating that temperatures within the shallow mantle 3.8 billion years ago were similar to today's. One rock type that is relatively abundant in the Archean record (> 2.5 b.y.) is rare after the Archean. This rock type, called komatiite, represents a very high temperature melt of the mantle.

Its predominant occurrence in the Archean shows that deeper sections of the mantle have continued to cool throughout the Earth's history.

Cooling of a once-melted planet implies that crystallization on a global scale has taken place. During crystallization, newly formed minerals selectively remove certain elements and leave others behind in the remaining liquid. Each crystallizing mineral leaves a distinctive chemical fingerprint. One might expect that global crystallization should imprint upon the rocks of the upper mantle the characteristic chemical signature caused by the removal of high-pressure mineral phases such as magnesium-perovskite or majorite-garnet. Instead, the chemical signature of the upper mantle, sampled worldwide by ocean-ridge basalt volcanism, is remarkably close to that expected for an undifferentiated Earth. Insofar as the upper mantle appears to be chemically differentiated, its prominent mineralogical signature is that of the low-pressure silicate mineral clinopyroxene. This implies that the prime control over mantle composition has been the removal of partial melts generated at relatively shallow depths in the mantle rather than the extraction of elements that are concentrated in high-pressure minerals.

The available geochemical evidence thus does not seem to support the conclusion that the Earth melted during its formation. This paradox poses a challenge to all those interested in the planet's history. A possible solution to the puzzle may be that, although the Earth was once melted, the record of this early melting was erased. One reason for suspecting this comes from studies of lunar rocks, returned with the Apollo missions. These rocks *do* show geochemical evidence that the Moon was extensively melted very early in its history. The Earth is a much more active planet than the Moon, and in some ways this activity may have erased the evidence for its early melting.

A possible candidate for the mechanism that accomplished this erasure is convective flow of the solid rocks of the Earth. In the early Earth, convection may have been driven by intrinsic mineralogical density differences, in addition to the thermal buoyancy that drives convection today. Seafloor spreading and subduction of tectonic plates are particular expressions of the present more-general convective flow. During the past ten years, there has been increasing evidence that convection in the Earth recycles crustal material into the deep interior. Convection serves as a giant blender, causing chemical heterogeneities in the mantle to be mechanically stretched and thinned, maybe even to the point that they disappear.

A more complete understanding of mantle convection is essential to the resolution of the paradox. Geochemists and seismologists at DTM are directing much of their attention to this problem. Last year, in *Year Book 87* (pp. 119–123), a "penetrative convection"

model was proposed by Paul Silver and Richard Carlson, in collaboration with Peter Olson of Johns Hopkins University, as a way to reconcile conflicting evidence as to whether the Earth's convective flow is layered (isolating the upper and lower mantle from one another) or if it penetrates the boundary between upper and lower mantle.

Additional geochemical evidence in support of this convective model has now been provided by our measurements of osmium isotopes. Working with Steven Shirey, Carlson, and Louis Brown, DTM Research Associate Richard Walker found a small but distinct difference in Os isotopic composition between suboceanic and subcontinental mantle. The osmium data support the established conclusion that convection is of little importance in the subcontinental mantle. In contrast, the suboceanic mantle data show that this region is enriched in $^{87}$Os, the product of radioactive decay of $^{87}$Re. It is a peculiar characteristic of the Re-Os isotopic system that basaltic oceanic crust has a tremendously greater Re-to-Os ratio than does the mantle. Consequently, Os in basaltic crust rapidly becomes radiogenic through Re decay. Walker has calculated that mixing roughly 5–10% basaltic crust 1.5–2 billion years old into depleted mantle will result in Os isotopic compositions similar to those observed for the present oceanic mantle. The mean age and relative abundance of recycled crust in Walker's calculations are similar to the mean mixing time and abundance predicted in the penetrative mantle convection model.

There is also evidence that this dominance of shallow melting, followed by convective mixing, is not a recent phenomenon but rather has taken place over the whole history of the Earth. Carlson has developed a model that interprets Nd isotope data, measured in collaboration with Shirey, to indicate that shallow melting of mantle rocks produced basaltic lavas within the first few hundred million years of the Earth's history. These are believed to have been oceanic basalts. If they had been continental basalts, remnants of ancient, buoyant continents should be found today, and they are not. The oceanic basalts have disappeared long ago, probably by subduction of the denser oceanic lithosphere into the mantle, but the chemical signature of their formation has been preserved.

These results illustrate the importance of mantle convection and will help in understanding the role it may have played in blending away the chemical heterogeneities that are expected to have resulted from extensive melting of the Earth early in its history. The Earth's interior may be uniquely homogeneous and relatively undifferentiated compared to the Moon's.

### *Epilogue: The Moral of the Story*

The universe tends to clump on a wide range of scales spanning

the domains of many specialties in the astronomical and planetary sciences. Ordinary scientists, limited by their typical superior intelligence, might find this discouraging. But they shouldn't. Just when it seems one's mental resources have been spread impossibly thin, there comes the illumination: Lo, it is all the same. Acquiring this insight does not require apprenticeship to a Zen master. It is freely given to all those who understand a few simple physical principles, of which the laws of conservation of angular momentum and energy are the most important. Acting together on distance scales varying from asteroids to galaxies, they guarantee that the falcon's gyre is bounded, and in those circumstances of most importance to all of us, the center does hold indeed.

*—George W. Wetherill*

The quotation at the start of this essay is from "The Second Coming," by William B. Yeats (1865-1939).

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## *Subduction, Volcanism, and Change in the Earth*

**by Julie Morris**

Standing on the continents, the Earth's surface seems simple—stable and static. Only occasionally, one learns of a volcanic eruption, usually far distant. But in reality, the Earth is scarcely quiescent, for continents are part of a cool shell wrapped around a hot, active interior.

One of the major goals of several scientists at the Department of Terrestrial Magnetism is to use volcanoes and earthquakes—surface expressions of the Earth's interior activity—as probes of the inner planet. Through geochemical and geophysical clues, we build up understanding of the Earth and the active processes that link the different levels of its interior with its surface.

The plate tectonic revolution of 25 years ago provided a broad picture of many of the physical processes by which the Earth operates and evolves. The uppermost layer, the lithosphere (including both the crust and the uppermost mantle), behaves rigidly and is broken up into about a dozen plates, as shown in Figure 1. Some plates are largely continental, others are largely oceanic, and many are both. The plates move about on the surface in response to heat-driven circulation, or convection, of material in the Earth's interior. New oceanic crust is continually forming from magma ascending from below at globe-girdling submarine mountain chains known as mid-ocean ridges. As the mid-ocean lavas cool and solidify, the plates continue to move away from the mid-ocean ridge, in response to the deeper convection.

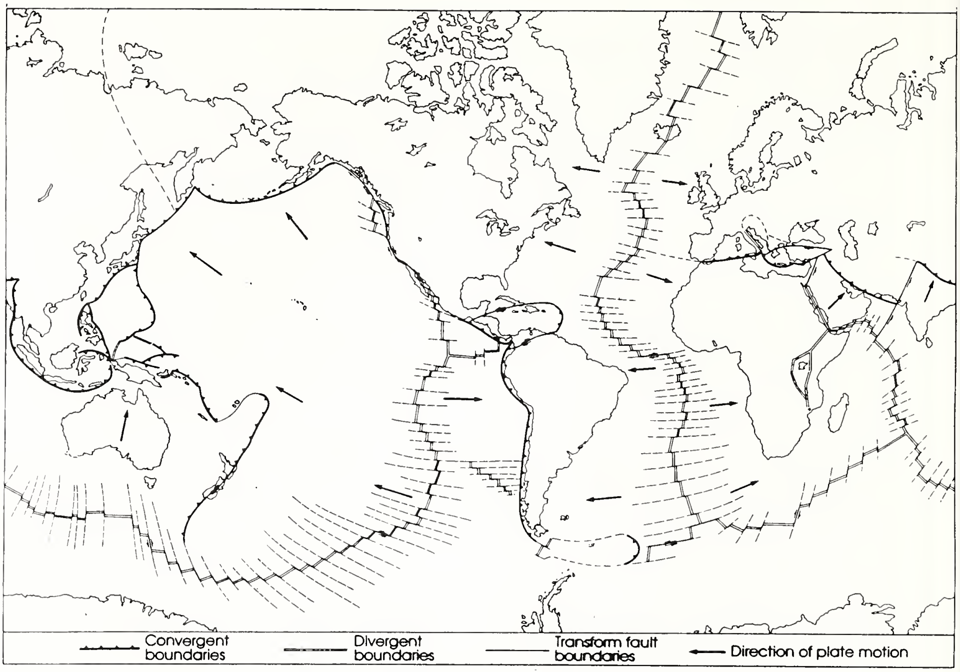


Fig. 1. Boundaries between the Earth's major plates. The thin double lines in the ocean basins indicate mid-ocean spreading ridges (divergent boundaries). New crust is created here and begins to move away from the ridges, indicated by the arrows. Solid heavy lines with teeth indicate the location of subduction zones (convergent boundaries). Oceanic crust, overlain by sediments, is returned to the mantle at these boundaries. Volcanic chains, or arcs, form above subduction zones, and are built upon both oceanic and continental crust. (From The Tasa Collection: Plate Tectonics, copyright 1984 by Tasa Graphic Arts, Tijeras, New Mexico.)

The moving plates converge in regions where one oceanic plate is subducted beneath another, where an oceanic plate is subducted beneath a continental, or, in a few cases, where continental plates collide. Eventually, the lithosphere formed at the mid-ocean ridges is carried back into the mantle at subduction zones (Fig. 2). Subduction occurs along some 30,000 km of convergent margins, at a rate of approximately 100 km per million years, leading to extensive transfer of surficial materials to the Earth's interior. Material is also transferred upward from the mantle to the surface in arcuate chains of volcanoes (volcanic arcs) that form above subduction zones, a process that leads to growth of continents.

The cycle of plate formation and subduction links the Earth's mantle, crust, hydrosphere, and atmosphere, and leads to chemical and thermal changes in the Earth. Between the time of its formation and subduction, the uppermost one kilometer of the oceanic plate reacts chemically with the Earth's atmosphere and oceans, and becomes covered with sediments derived from the continents. Some of the subducted crustal materials are returned to the

surface in volcanic arcs, while others are apparently subducted into the Earth's deep interior.

The study of subduction zones requires cooperation and interaction between scientists of many different disciplines. The very existence of subduction zones was first documented by seismologists who mapped the inclined plane of earthquakes (Fig. 2) and attributed the earthquakes to the interaction of cold, dense, brittle plates with the hotter mantle. DTM geophysicists L. Thomas Aldrich, David James, Alan Linde, I. Selwyn Sacks, and Paul Silver have all been involved in studies of subduction zones. They have investigated the distribution, duration, and mechanisms of earthquakes, the deformation of the Earth's surface associated with plate convergence, the geometry, depth, and states of stress of the subducted slab, and the temperatures in the subducting plate and the overlying mantle. DTM geochemists Louis Brown, Richard

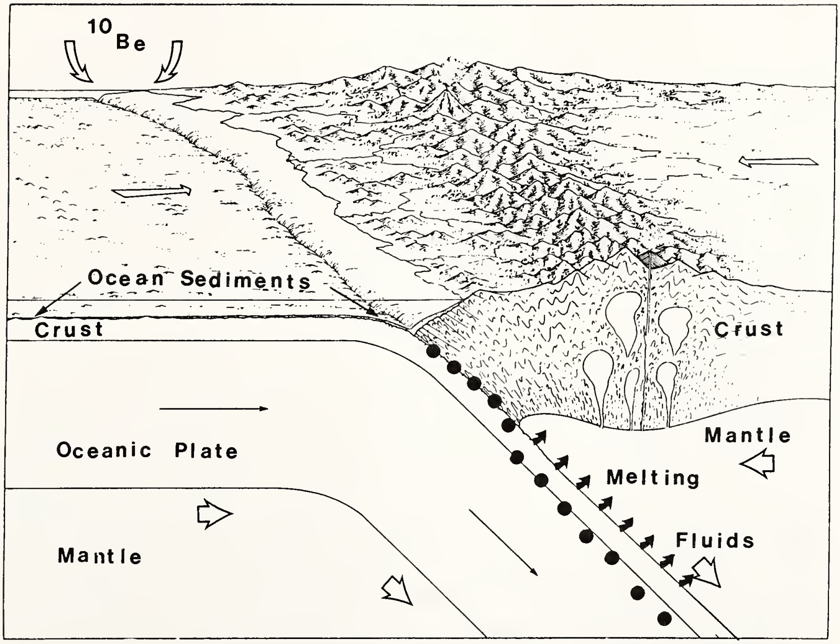


Fig. 2. A cross section of a volcanic arc, showing the subducting oceanic plate (including lithosphere and crust) and its associated sediments (which host $^{10}$Be), and the overlying volcanic chain. The distribution of earthquakes (shown as circles) along an inclined zone beneath the volcanoes was the first evidence for plate subduction. The shallow earthquakes are often very hazardous. Small solid arrows leaving the subducted oceanic plate show the transfer of aqueous solutions (fluids) from the slab to the mantle. Large, open arrows show convection in the oceanic mantle and the "wedge" of mantle beneath the volcanic arc. This sketch shows volcanoes amalgamating through time to form mountain chains which eventually become new continental crust. Often, formation of gold, silver, copper, and tin deposits accompanies volcanism and continental growth. (From The Tasa Collection: Plate Tectonics, copyright 1984 by Tasa Graphic Arts, Tijeras, New Mexico.)

Carlson, Julie Morris, Steven Shirey, and Fouad Tera have all participated in studies of subduction-related volcanism, both modern and ancient. The geochemical studies have focused on the unique chemical composition of material derived from the subducted plate, the persistence of this subducted "signature" through time in lavas derived from both the deep and shallow mantle, the net effect of crustal recycling on the geochemical evolution of the Earth, and the connections between subduction and volcanism in ancient times. The depth and breadth of the DTM studies are leading to a much clearer picture of the links between the subducted oceanic plate, the overlying volcanic arc, and the deep mantle.

Initially, most researchers thought that the subducted slab simply melted to make the lavas that erupt in volcanic arcs. More-recent work suggests that lavas are formed by melting in the "wedge" of mantle above the subduction zone. In this view, the exact link between volcanism and the subducting plate is obscure, and remains hotly debated. A project begun at DTM ten years ago was designed to study what happens to the subducted plate in volcanism along convergent margins. Fouad Tera and Selwyn Sacks suggested that $^{10}$Be (beryllium of atomic mass 10) could be used to show that sediments carried on the oceanic plate are subducted and are subsequently involved in magma formation—an important and somewhat intractable question. The subsequent $^{10}$Be work at DTM led to a clear, positive answer, one that has proven to be a key to understanding many of the physical and chemical processes affecting the subducted plate during its passage beneath the volcanic chains.

$^{10}$Be has been shown the perfect tracer for the subduction of oceanic sediments. It is made in the atmosphere when cosmic rays break apart atoms of oxygen and nitrogen. The newly formed isotope is rained out of the atmosphere and much of it is deposited in the oceans. The $^{10}$Be in seawater adheres to the settling clay particles and so becomes concentrated in oceanic sediments. In effect, nature has created the ideal experiment—tagging the sediments with very high concentrations of $^{10}$Be and allowing us to trace the passage of these tagged sediments down the subduction zone and back to the surface in volcanic arcs. $^{10}$Be is also radioactive, with a half-life of 1.5 million years. This means that it remembers only the events of the last 10 million years, and can thus be used to study processes operating in the subduction zone in the present and the geologically recent past.

Measurements of $^{10}$Be are not easy, as concentrations in volcanic rocks are quite low (1–20 million atoms per gram) and difficult to measure. In fact, to use this tracer, it is necessary literally to measure atoms of $^{10}$Be in the rock. The technique uses a particle accelerator (a tandem Van de Graaff accelerator) coupled with a large mass spectrometer. The technique was developed by Roy Middle-

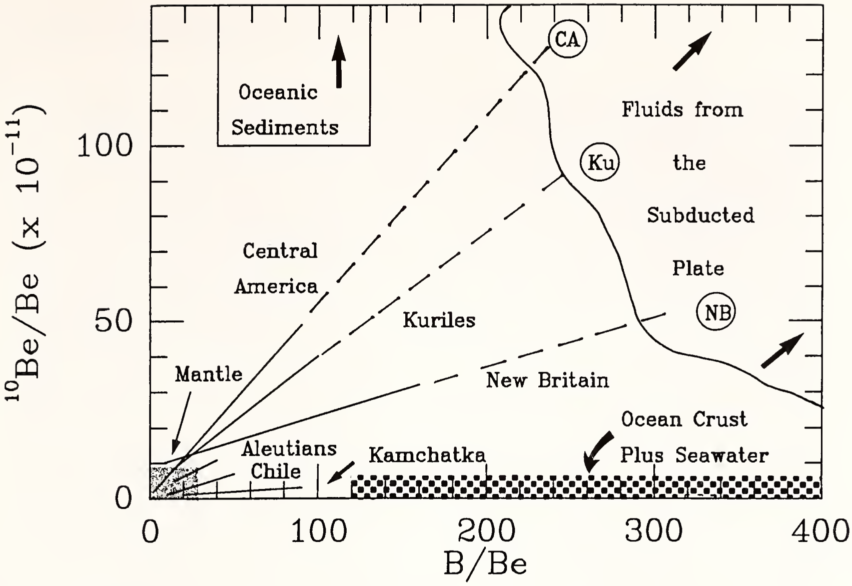


Fig. 3. Measurements of volcanic samples from various regions (solid lines). Plotted are ratios of elemental boron to beryllium (B/Be) vs. ratios of $^{10}$Be to total beryllium ($^{10}$Be/Be).

If all the volcanic material were of direct mantle origin, the data would fall in the box area at lower left (very low concentrations of $^{10}$Be and B). Also shown are typical characteristics of subduction-related materials that may compose part of the volcanic lava—oceanic sediments (box at upper left, high $^{10}$Be) and ocean crust plus seawater (region at lower right, high B). The actual composition of subduction-related material incorporated in the lavas must plot on the dashed-line extensions of the solid-line, measured trends. See text for analysis.

ton and Jeff Klein of the Tandem Accelerator Laboratory at the University of Pennsylvania, in conjunction with DTM staff member Louis Brown. The DTM initiative to measure $^{10}$Be, together with the outstanding collaboration with the Tandem Lab, has been crucial to the development of accelerator mass spectrometry. This new capacity to make low-concentration measurements of rare isotopes has opened up important new areas of scientific study, especially of processes operating on the Earth's surface.

It recently became possible to combine $^{10}$Be data with measurements of the more abundant, stable isotope $^{9}$Be. The ratio of the two isotopes is a rigorous indicator for the addition of oceanic sediments to the mantle wedge and thence to the arc lavas. Collaborating with W. P. Leeman from the National Science Foundation, and with DTM postdoctoral fellow Jeff Ryan, we now also employ boron (B) concentration data. Boron, like $^{10}$Be, is strongly enriched in oceanic sediments, and is observed in high concentrations in subduction zone volcanoes. The combination of B with the Be isotopes has proven to be a very strong tool for understanding subduction zone processes, for reasons shown in Figure 3.

Figure 3 is known as a mixing diagram. Plots of B/Be vs. $^{10}$Be/Be

of volcanic samples from different regions are seen to form straight lines. (The solid-line segments are the actual, measured data.) The lines reveal the mixing of material from two sources: (1) mantle material, having low $^{10}Be/Be$ and B/Be, as in lower-left region of diagram, and (2) material associated with the subducted plate. The compositions of the latter component must plot on the dashed-line extensions to upper right; note that the values are higher in B/Be than those typical of oceanic sediments (shown in upper-left box).

This is an interesting result, because it indicates that what is happening is not the simple addition of subducted oceanic sediments to the mantle. Rather, the process that transfers subduction-related material to the mantle is somehow separating B from $^{10}Be$, even though both are concentrated in the sediments. This separation cannot result from melting of the sediments, as both elements behave (partition) similarly during melting. Moreover, lavas from volcanoes that overlie deep subduction zones (regions where the slab has already been chemically processed at shallower levels) still contain $^{10}Be$, indicating that the sediments persist to depth in the mantle and arguing against wholesale melting of the slab's oceanic crust and sediments. The inference that sediments do not melt constrains the temperature of the subducted slab down to 100-km depth to be less than about 750°C, an important piece of information for understanding the thermal structure of the slab and mantle. At these relatively low temperatures, the oceanic crust will remain physically intact during and after its passage through the subduction zone beneath the volcanoes. In fact, recent work by Thomas Jordan of M.I.T. and by DTM staff member Paul Silver indicates that the subducted plate often penetrates into the mantle to depths greater than 650 km (perhaps even to the core-mantle boundary), thereby carrying elements from the surface into the lower mantle, helping drive deep mantle convection, and providing clues about the density structure of the deep interior.

The subduction-related lava component in Figure 3 is probably an aqueous solution rather than a melt or solid. Water that becomes bound in oceanic crust and sediment particles through reaction with seawater is driven off as the cold slab travels to deeper and hotter depths in the mantle. This water forms a brine-like solution which carries certain elements (e.g. boron, uranium) to the overlying mantle and leaves others (i.e., Be) behind. We are now engaged in a project to determine just how other elements, especially those that produce heat through radioactive decay, behave during subduction. Those elements that do not leave the slab in aqueous solution can be subducted to depth, and can change the chemistry of the Earth's interior.

The brine-like solutions associated with subduction may be a very effective mechanism for concentrating elements like gold, silver,

and copper into economically significant deposits. Most fundamental, however, is the realization that the transfer of water from the subducted plate to the overlying mantle is probably the key to volcanism at convergent margins. Compared to lavas from other tectonic settings, those erupted in volcanic arcs have high water contents. These large amounts of water, derived ultimately from the subducted oceanic crust, can explain the often violently explosive nature of the volcanism. Probably, the water released from the subducted plate triggers the melting and magma formation in the mantle wedge. This occurs because the presence of water lowers the melting temperature of the mantle, as seen in many experiments conducted at Carnegie's Geophysical Laboratory and elsewhere. At convergent margins, where continued subduction of cold oceanic crust chills the mantle, the presence of water may be necessary to permit melting and volcanism at all.

DTM's Selwyn Sacks is using a combination of geophysical techniques to study the distribution of water-rich brines and melts in the mantle. Studies of the attenuation (absorption of seismic energy) characteristics in the mantle above subduction zones have been especially informative. Comparison of attenuation measurements of mantle rocks performed in the laboratory with measurements of those in subduction zones (made in the field) indicates that the temperature in the mantle wedge is cooler than that required to melt the rocks in the absence of water. The temperature is high enough, however, to permit melting in the presence of excess water. The data also show that regions of melt large enough to change attenuation characteristics are not present in the mantle. These observations suggest that water influx from the slab triggers localized melting and the ascent of magmas to the Earth's surface on geologically short time scales—less than 200,000–300,000 years. This interpretation is consistent with measurements of relatively short-lived parent-daughter isotopes by our collaborator J.B. Gill, University of California at Santa Cruz. The critical role of water in permitting volcanism at arcs means that growth of the continents today is possible because seawater is carried into the Earth's interior at subduction zones.

Another striking aspect to the Be-B data (Fig. 3) is that the data points for each volcanic arc form a simple straight line having high correlation coefficients ($r^2 > 0.86$). This consistency is unusual in the geochemical literature describing volcanic arcs, which are widely regarded as very complicated systems involving mixtures of many different materials (slab, sediment, different types of mantle, crust). The complexity of arc geochemistry, in fact, has generally prevented any clear understanding of the processes responsible for the formation of arc volcanoes. The simple systematics in Figure 3, however, allow us to uniquely identify and isolate the contribution from the subducted plate and the associated chemical

consequences. In each case, the fluid derived from the subducted plate has a nearly constant composition. This is surprising and important, as the sediments and oceanic crust can have highly variable compositions, especially with respect to the radioactive $^{10}Be$.

It may be that the sediments are mechanically mixed and shuffled during subduction to minimize the sediment variability. Alternatively, the process of dissolving elements into the fluid may allow the elements and isotopes to mix towards a constant composition. Regardless, these results indicate that, contrary to conventional wisdom, the geochemical complexity of arc lavas is probably not due to the effects of the subducted component. Rather, scientists studying magma formation above subduction zones will need to investigate more closely the effects of a chemically variable mantle and of interaction of the magmas with the crust during their ascent to the surface.

A major conclusion of this work is that subduction zone processes appear to be more regulated and consistent than previously thought. They therefore leave clues that geochemists and geophysicists can build into a coherent picture. At DTM, geophysicists are developing increasingly sensitive seismic techniques to study convergent margins, and geochemists are developing new geochemical tracers (for example, the Re-Os isotope system; see p. 110) for monitoring physical processes. Continuing discussions between these two groups promote an interdisciplinary way of thinking, significantly improving our ability to understand the complex Earth. A clear understanding of how subduction zones link the Earth's surface and its interior, and create changes in both, will provide a secure base from which to look into the past, to understand the Earth's change through time.

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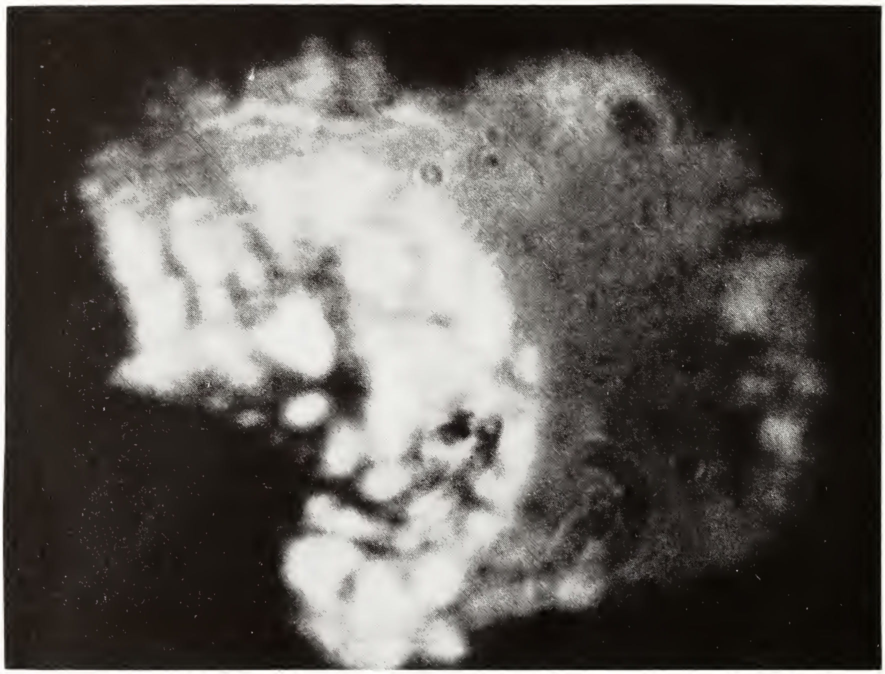
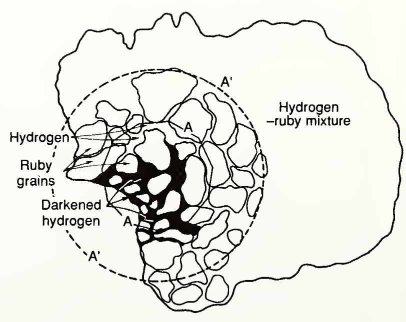
*Geophysical Laboratory*



Photomicrograph of solid hydrogen and $Al_2O_3$ ruby sample within the high-pressure diamond-anvil cell, obtained during a recent experimental run by Ho-kwang Mao and Russell Hemley. The hydrogen veins toward the center *A* (see map) appear darkened and are nearly opaque at the pressure of 250–300 GPa. The opacity at that high pressure is tell-tale evidence of predicted metallization transition. (From *Science 244*, 23 June 1989, pp. 1462-1465, copyright 1989 by the American Association for the Advancement of Science.)



## *The Director's Essay*

Since the founding of the Geophysical Laboratory, its research programs have emphasized physicochemical investigations of earth materials and how the properties of these materials are related to important earth processes, "including the flow of rocks, the destruction and genesis of minerals, the functions of included water and gases, the internal transfer of material, the origin of ore deposits, the evolution and absorption of heat, and other phenomena that involved the effects of temperature, pressure, tension and resultant distortion upon chemical changes and mineralogical aggregations."* In reviewing the research activities of the past year, one can see that much of the current work is related to this general theme. There are, however, other areas of interest to our staff that were not anticipated 85 years ago—e.g., the application of stable isotope analysis to problems in biogeochemistry, the synthesis of minerals that could have formed in the solar nebula, and the transformation of hydrogen to new forms that may provide important information about the interiors of the giant planets.

This summary can only review a portion of the research being conducted at the Geophysical Laboratory. Although it is divided into four sections—experimental petrology and geochemistry, biogeochemistry, mineral physics, and field and observational petrology—these divisions do not totally represent how research is conducted or how staff members interact with each other and with scientists from other institutions. There is extensive collaboration across the rather diffuse boundaries between these subdisciplines, a situation very much encouraged by the director. For more details about specific research topics, the reader is referred to the *Annual Report of the Director of the Geophysical Laboratory*, published separately.

*Arthur L. Day's review of the 1902 report of the advisory committee on geophysics that led to the founding of the Geophysical Laboratory (*Year Book 26*, 1927).

*Experimental Petrology and Geochemistry*

Experimental petrology and geochemistry have always been fundamental areas for research at the Geophysical Laboratory, and they remain so today. The kinds of experiments being performed are changing with time and are making use of new theories, new techniques, and new instrumentation being developed here and elsewhere.

*Element Partitioning and Phase Transitions in the System Mg-Fe-Si-O at High Pressure and Temperature.* Currently, a major question in geoscience involves the nature of the seismic discontinuties in the Earth's mantle at 400 and 670 km—whether they are a result of phase changes, changes in composition, or both. Predoctoral fellow Yingwei Fei, working with Ho-kwang Mao and Bjørn Mysen, has done experiments on element partitioning and phase relations in the system Mg-Fe-Si-O at high pressure and high temperature. (The principal components of the Earth's mantle are MgO, FeO, and $SiO_2$.) Phase relations in this system are of great interest to geochemists and geophysicists because the 400-km and the 670-km seismic discontinuities may reflect the phase transformations of olivine ($\alpha$) to $\beta$-phase (modified spinel), and of spinel ($\gamma$) to perovskite plus magnesiowüstite, respectively.

The phase relations can be established in two ways. One is to determine phase boundaries in pressure-temperature-composition space; the other is to determine precisely the phase boundaries of pure phases and the mixing properties of each solid solution. The phase relations in binary or multi-component systems can then be calculated.

Solid solutions in the Mg-Fe-Si-O system include (Mg,Fe)O (magnesiowüstite), $(Mg,Fe)_2SiO_4$ (olivine, $\beta$-phase, spinel), and $(Mg,Fe)SiO_3$ (pyroxene, ilmenite, perovskite). These solid solutions form four pairs of coexisting phases, each including magnesiowüstite (Mw): Mw-olivine, Mw-$\beta$-phase, Mw-spinel, and Mw-perovskite. The solution properties of each individual phase may be derived from the element distribution data by considering the distribution of an element between two solid solutions as an exchangeable reaction. The purpose of Fei's study was to derive the mixing properties of each solution by determining experimentally the distribution of Mg and Fe between coexisting solid solutions at various pressure and temperature conditions and to establish phase relations in the system.

Figure 1 shows Fei's computed isothermal phase relations in the binary system $Mg_2SiO_4$-$Fe_2SiO_4$ at temperatures of 1473K and 1873K and pressure to 300 kbar. This calculated diagram is in good agreement with those determined previously by others.

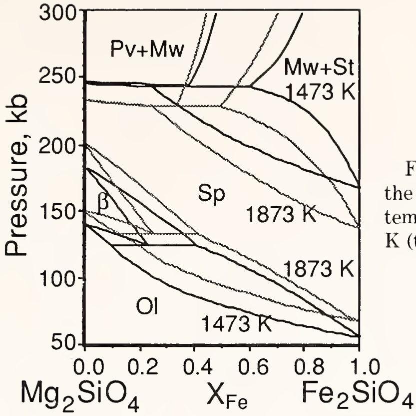



Fig. 1. Calculated isothermal phase relations in the binary system $Mg_2SiO_4$ and $Fe_2SiO_4$ at temperatures of 1473 K (the heavy lines) and 1873 K (the light lines) and pressure to 300 kbar.

The thermodynamic data base evaluated from experimental data can be used not only for reproducing the existing experimental results, but also for interpolation and even, with caution, extrapolation. It allows us to explore phase relations in the system in various ways. For instance, one may construct phase relations in pressure-temperature space or in pressure-composition space. In the mantle model of peridotitic composition where olivine $(Mg_{0.88}Fe_{0.12})_2SiO_4$ is the major component, the phase diagram of this olivine indicates that the depth and width of the phase transformations of olivine to β-phase and of spinel to perovskite plus magnesiowüstite are compatible with the seismic observation of the 400-km and the 670-km discontinuity, respectively. The density profile of the mantle can be simulated by varying chemical composition along the assumed geotherm. However, to make the comparison between the calculated and observed profiles, at least Ca and Al should be included in the system. Experimental determination and computer simulation of phase relations in the extended system can provide critical constraints for models of the Earth's mantle.

*Igneous and Metamorphic Facies of Potassium-Rich Rocks.* Hatten Yoder is pursuing a long-term interest in the igneous and metamorphic facies of potassium-rich rocks, with emphasis on coexisting assemblages in the kalsilite-forsterite-larnite-quartz system at 950°C and 2 kbar with and without $H_2O$.

The wide variety of potassium-rich igneous and metamorphic rocks appears to result primarily from the great diversity of bulk composition and from the large number of reactions between phases. The mineralogical complexity of the final products probably results from incomplete or failed reactions as the magmas cool. For this reason, Yoder seeks to establish experimentally a stable array of assemblages with which observed and alternative assemblages can be compared.

The principal minerals involved in *anhydrous* potassium-rich

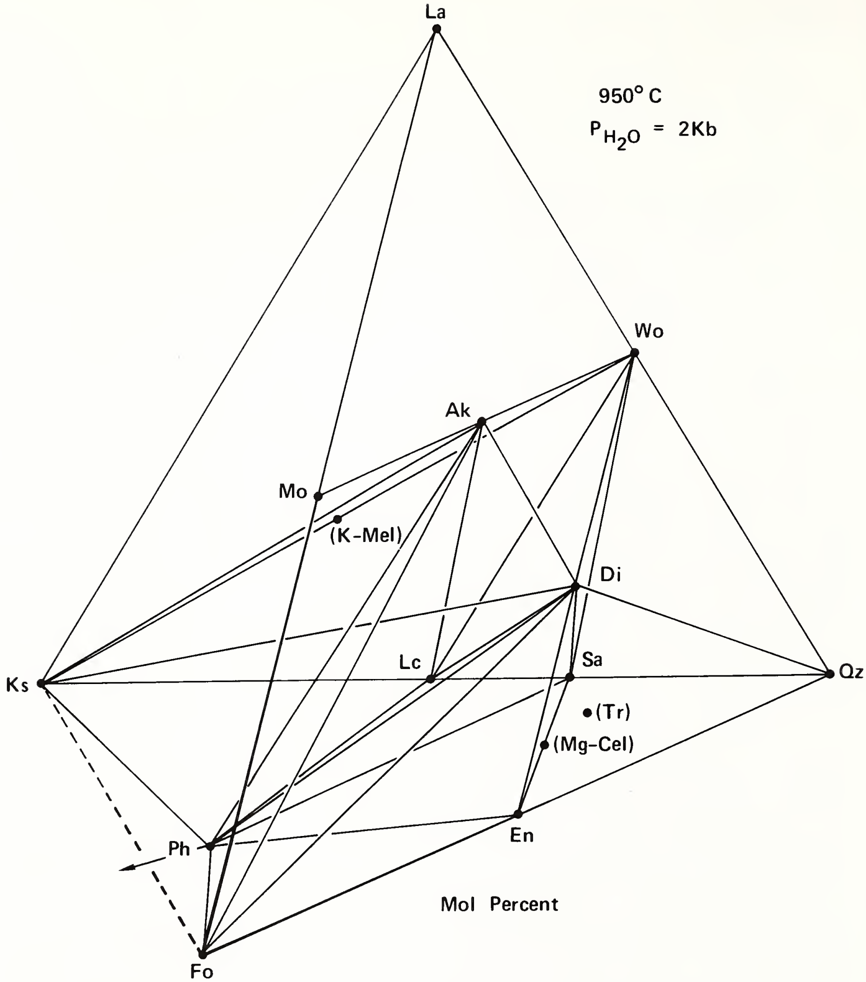



Fig. 2. Potassium analogue of the extended normative, basalt tetrahedron Ks–La–Fo–Qz exhibiting stable joins determined experimentally at 950°C and 2 kbar.

| | |
|---|---|
| Ak, akermanite | Lc, leucite |
| Di, diopside | Mer, merwinite |
| En, enstatite | Mo, monticellite |
| Fo, forsterite | Ra, rankinite |
| K-mel, potassium melilite | Sa, sanidine |
| Ks, kalsilite | Qz, quartz |
| La, larnite | Wo, wollastonite |

rocks are displayed in Figure 2. The tetrahedron is the potassium analogue of the extended basalt tetrahedron wherein kalsilite replaces nepheline. The joins connecting coexisting phases were established by Yoder's experiments of five days duration at 950°C and 2 kbar. Stable assemblages were determined by reacting natural minerals close to end-member composition, synthetic end-members, or both, in compatible and incompatible combinations. The experiments were carried out in an internally-heated, gas-media,

high-pressure apparatus. Over sixty mixtures of compatible and incompatible phases were reacted to establish the stable joins for both the anhydrous and hydrous tetrahedrons at isothermal, isobaric conditions. The conditions 950°C and 2 kbar were chosen so that there was adequate pressure to stabilize the appropriate hydrous minerals, and a sufficiently high temperature to be at or near the beginning of melting, yet above the stability of the amphiboles.

Yoder's results provide a consistent ensemble of assemblages from which compatible and incompatible mineral assemblages in K-rich rocks can be determined. The complexity of the alkaline rocks appears to result primarily from variations in bulk composition; however the large number of potential reactions between phases contribute to further complexity when the successive reactions are incomplete. Because of the large number of phases in alkaline rocks, the textural relations (e.g., rimming, morphology, and zoning) may be of great importance in revealing the sequence of reactions.

*Experimental gas loading.* Studies of hydrothermal systems constitute an extremely important part of earth science research. Many processes, including the formation of ore deposits, are involved with hydrothermal systems, and it is essential that methods be developed to simulate hydrothermal conditions in the laboratory. Staff members John Frantz and Thomas Hoering, working with postdoctoral fellows Yi-gang Zhang and Donald Hickmott, have developed techniques for experimentally loading and analyzing gases for application to synthetic fluid inclusions.

Experimental studies of equilibria between minerals and mixed volatiles under hydrothermal conditions have long been a research focus for many experimentalists. One of the principal difficulties in experimentally investigating reactions between minerals and mixed volatiles under hydrothermal conditions is loading the experimental charges with gas mixtures of known composition. In the past, gas loading was accomplished primarily by the addition of solid compounds that produced volatiles in the experimental charge. For example, silver oxalate was used as a source of carbon dioxide; iridium carbonyl, to produce carbon monoxide; oxalic acid, as a source of carbon dioxide, water, and hydrogen; chromium nitride, to produce nitrogen or ammonia if used in conjunction with an external oxygen buffer; acetic acid, as a source of carbon dioxide and methane; and graphite, to produce carbon dioxide, carbon monoxide, and methane when used in conjunction with an external oxygen buffer. The applications of these procedures have been instrumental in many studies important to our understanding of equilibria between metamorphic mineral assemblages and mixed volatiles. The new gas loading technique has been demonstrated successfully by growing synthetic fluid inclusions in the

$CO_2$-$CH_4$-$H_2O$ system at high temperatures and pressures and analyzing the gases in the capsule by gas chromatography. High-temperature, high-pressure intergranular fluids in the Earth's mantle and crust have had a profound influence on the evolution and resulting mineral petrogenesis of igneous and metamorphic rock suites. The synthetic fluid inclusion method combined with the gas-loading techniques of Frantz and colleagues have proven quite effective in the determination of the molar volumes, liquid-vapor curves, isochores, and low-temperature phase relations of C-O-H gas mixtures.

*A new class of fluid inclusions.* As part of his research, postdoctoral fellow Craig Schiffries has described a new class of fluid inclusions, one characterized by the absence of a liquid phase at 20°C.

A wide variety of geological phenomena are governed by interactions between fluids and rocks at elevated temperatures and pressures. Studies of fluid inclusions provide important constraints on the chemical composition of crustal fluids and the physical conditions of fluid-rock interactions. The new class of inclusions hold special interest because they display the following properties: (1) Although they do not contain a liquid phase at 20°C, the inclusions homogenize to an aqueous liquid at elevated temperatures; (2) Initial melting occurs at a reaction point (+29°C), rather than a eutectic point as commonly assumed ($T_E = -52$°C for the system $CaCl_2$-$NaCl$-$H_2O$); (3) Ice is absent in the subsolidus assemblage despite the high $H_2O$ contents of the inclusions, while at room temperature, most of the water occurs as structurally bound $H_2O$ in hydrate minerals and a relatively small amount occurs in a low-density vapor phase; (4) The most abundant daughter minerals in the subsolidus assemblage are antarcticite ($CaCl_2 \cdot 6H_2O$) and a second hydrate that may be a new mineral; (5) The fluid compositions fall outside the compositional limits defined by previous studies of natural fluid inclusions.

The inclusions described here occur in quartz from a mafic pegmatoid in the Bushveld Complex. Similar inclusions probably occur in other geological environments, but they may be overlooked or misinterpreted because their solidus temperature is above 20°C. The fluids are characterized by a high Ca/Na ratio and a very high concentration (greater than 52 wt %) of total dissolved solids.

### *Biogeochemistry*

Interpretation of stable isotope distributions has become a primary tool for biogeochemists in the Geophysical Laboratory, and the following summary attempts to show how stable isotopes are being used in a variety of applications.

*Nitrogen Isotope Tracers.* Marilyn Fogel, with Noreen Tuross and Douglas Owsley of the Smithsonian Institution, have studied nitrogen isotope tracers of human lactation in modern and archeological populations. Variations in the stable isotope ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) are useful for paleodietary analysis of archaeologically derived skeletal material. Because plants and animals have distinctive isotopic signatures, the isotopic composition of humans can therefore be correlated with diets. For example, the C isotopic composition of corn is distinct from other crop plants, such as beans or squash. The difference in the $\delta^{13}C$ value is due to the operation of a different photosynthetic pathway (C-4 photosynthesis) that occurs in corn relative to that which is operational in most other higher terrestrial plants (C-3 photosynthesis). Accordingly, the introduction of corn (maize) into the diet of prehistoric North American Indians has been traced with stable C isotope ratios of the protein collagen preserved in fossil bones.

One of the major questions in anthropology is how the introduction of agriculture affected weaning and birth intervals in prehistoric peoples. Some have hypothesized that, before agriculture, humans nursed their infants longer and, concomitantly, birth intervals were longer. They assume that with the introduction of agriculture, mothers weaned their babies onto alternative food sources at a younger age, and were thus able to give birth again in a shorter time interval. These hypotheses are difficult to test in modern populations, and seemingly would be impossible to test in prehistoric ones. Fogel and colleagues have investigated whether breast milk has a unique isotopic signature that can be used to trace lactation in humans. Infant nutrition in both modern and fossil populations was studied with carbon and nitrogen isotopic tracers. The hypothesis that nursing infants exist one trophic level up on the food chain from their lactating mothers, and thus that protein from infant tissue should be enriched in $^{15}N$ relative to the mother's protein, was tested.

In their study of contemporary mothers and infants, Fogel and colleagues sampled and analyzed fingernails. Fingernails are a rapidly synthesized tissue easily obtainable from both infants and their mothers. Numerous studies on nail growth have documented that in healthy, growing infants, fingernails require 2–3 months time to grow from cuticle to finger tip. One infant and her mother were sampled from birth to fifteen months in a longitudinal study, in addition to sixteen separate mothers and their infants in a cross-sectional study. In all cases, the isotopic composition of the nursing infants' fingernails was enriched in $^{15}N$ compared to that of the mothers over the age range from three months until several months after alternate food sources were introduced. A decrease in the infant $\delta^{15}N$ values toward those of their mothers—seen in

every sample tested—correlates with the introduction of alternative nitrogen sources: infant formula, milk, dairy products, and meat. Carbon isotopic compositions of infant fingernails (−17.5‰) were nearly identical to those of their mothers and were not useful for tracing human milk sources. Fogel and colleagues thus conclude that a clear tracer of lactation is established in the protein of fingernails.

The results from their analysis of prehistoric human populations demonstrate that when a suite of individuals with known ages is analyzed, then the $\delta^{15}N$ of collagen preserved in bone can be used as a tracer of infant nutrition: breast feeding, weaning, and the introduction of alternate food sources. Nursing and weaning practices in the pre- and post-agricultural Indian populations studied were not significantly different from one another. In both populations, alternate food sources were introduced at 18–20 months, and breast milk became less important in the diet. Full realization of the application of this technique will require the analysis of well-characterized collagen from large, skeletal populations.

*Nitrogen Isotropic Distribution in the Black Sea.* David Velinsky, Marilyn Fogel, and Bradley Tebo are looking at dissolved nitrogen isotopic distribution in the Black Sea. The Black Sea is the world's largest present-day anoxic marine basin. As a result of intense water column stratification, the flux of oxygen to the bottom waters is not sufficient for the complete oxidation of surface-derived organic matter. Below approximately 200 m, bacteria use alternate electron acceptors, including iron and manganese oxides, nitrate, and most importantly sulfate, to oxidize organic matter during respiration. Because sulfate is the most abundant oxidant after oxygen, microbial respiration is dominated by sulfate reduction in the deep waters and sediments.

During the oxidation of organic matter coupled to sulfate reduction, organically bound nitrogen is converted to ammonium. These reactions, coupled with the sluggish mixing of Black Sea deep waters, result in the buildup of ammonium in the waters below approximately 100 m. As the ammonium diffuses upward in the water column across the oxygen-sulfide boundary at 200 m, it undergoes important transformations that affect biological production and possibly also trace metal distributions. For example, ammonium can serve as an energy source for aerobic chemosynthetic production of organic matter. In the process of nitrification, chemoautotrophic bacteria convert ammonium to nitrite and nitrate, which can subsequently be reduced to nitrogen gas via denitrification in tightly coupled reactions. In addition, because of the broad zone of low oxygen concentration just above the oxygen-sulfide interface observed during their 1988 expedition to the Black Sea, Velinsky and colleagues postulate that nitrate can serve as an electron

acceptor for both ammonium and dissolved manganese oxidation. Thus there are potentially both aerobic and anaerobic processes taking place near the interface that can consume ammonium and limit its availability as a nutrient in the overlying waters.

In summary, two distinct processes appear to be occurring near the 200-m interface of the Black Sea: (1) denitrification and (2) chemosynthetic production of organic matter. Both processes result in distinct isotopic ratios for both ammonium and nitrate. Below the nitrate concentration maximum, the concentration of nitrate decreases due to denitrification. This is further evidenced by the increase in $^{15}N$ below the nitrate concentration maximum. Ammonium concentrations start to increase because sulfate reduction and related ammonium production were faster then both transport and consumption. However, results of their modeling show that there is a net consumption of ammonium most likely associated with bacterial chemosynthetic production near the interface. As the bacteria consume ammonium, the residual ammonium becomes increasingly enriched in $^{15}N$.

*Precipitation of Manganese Oxides by Marine Bacteria.* Predoctoral fellow Kevin Mandernack, Marilyn Fogel, Bradley Tebo of Scripps, and Jeffrey Post of the Smithsonian Institution have performed mineralogical and oxygen isotope analyses of manganese oxides precipitated by spores of a marine bacterium. Manganese(II) oxidation in the environment is generally catalyzed by bacteria. The mechanism of this process, however, is poorly understood, as are the products of microbial Mn oxidation. It is generally believed that the concentration of Mn(II) in seawater and the oxidation state of marine Mn oxides are controlled by the rapid precipitation of hausmannite ($Mn_3O_4$), which can be microbially mediated. The $Mn_3O_4$ rapidly undergoes abiotic disproportionation to $MnO_2$ because of low Mn(II) concentrations typically found in the marine environment.

It is generally believed that manganese oxidation occurs in two steps. In the laboratory at 25°C, the initial product is hausmannite, which can spontaneously protonate to manganite, γ-MnOOH. Theoretically, $MnO_2$, which has an oxidation state of 4+, results from a disproportionation of $Mn_3O_4$. In laboratory experiments by Mandernack and colleagues lasting up to nine months, however, the highest oxidation state observed was 3+ except under more extreme conditions of high temperature or pH. This fact is rather enigmatic considering that manganese in the oceans is usually highly oxidized. It is possible that more-oxidized phases do not form in the experiments because of high concentrations of dissolved Mn(II).

Representative strains of bacteria that could be responsible for Mn oxidation in the ocean have been observed to precipitate

high-oxidation-state manganese oxides (≥3+), even at high dissolved Mn(II) concentrations in solution. Because of uncertainties that persist in the mechanisms of Mn oxide formation by these bacteria, Mandernack *et al.* examined these processes with oxygen isotope tracer and x-ray powder diffraction studies on an array of oxides precipitated by SG-1 spores.

Summarizing their results, both x-ray powder diffraction and isotopic tracer studies confirm that manganese oxides are precipitated by a different mechanism than that proposed previously for chemical precipitates and for spore-catalyzed oxides. No traces of hausmannite or manganite were found in minerals precipitated at low Mn concentration. If hausmannite were the initial product in the formation of the higher oxidation state oxides, oxygen bonds in the crystal lattice must be broken and re-formed during the rearrangement of structure to buserite or todorokite. The involvement of molecular oxygen is indicated by isotopic ratios of these two oxides, rather than in the initial formation of hausmannite itself. With better quantitative mineral identification, it should be possible to determine whether Mn oxidation mechanisms for chemically driven systems are the same as those catalyzed by living organisms.

*Carbon Reduction Technique for Oxygen Isotope Analysis.* Zachary Sharp and James O'Neil have developed a laser-based carbon reduction technique for oxygen isotope analysis of silicates and oxides.

Stable isotope analysis is one of the most valuable geochemical techniques available for constraining the conditions of formation and alteration in most rock types. However, the methods for extracting oxygen from silicates and oxides have remained relatively unchanged over the past 25 years. Large sample sizes are required for analysis, and nearly all spatial resolution is lost. Fine-scale variations in the $\delta^{18}O$ of oxides and silicates cannot normally be determined. In contrast, other geochemical techniques have been used successfully to determine major, minor, and trace element concentrations, crystal structures, and isotopic compositions (i.e., U-Th-Pb, $^{40}Ar/^{39}Ar$, $\delta^{34}S$) on a mm scale.

The natural variations in the $\delta^{18}O$ of minerals are so small that analytical techniques of very high precision are required to distinguish them. Two conventional analytical methods have been developed that are capable of analyzing the $\delta^{18}O$ of oxides and silicates at the required high level of precision necessary: (1) fluorination and (2) carbon reduction.

Fluorination of minerals at moderate temperatures (200–650°C) liberates $O_2$, which is converted to $CO_2$ and subsequently analyzed by conventional isotope ratio mass spectrometry. The fluorination method is applicable to all but the most refractory minerals, but relatively large sample sizes of 5–30 mg are generally required to obtain accurate and reproducible results. Samples as small as

1 mg can be analyzed only with extreme care and by assigning a somewhat arbitrary blank correction.

The carbon reduction method involves the high temperature (1000–2400°C) reduction of minerals to carbides or native elements and CO with varying amounts of $CO_2$. The evolved CO is converted to $CO_2$ and analyzed. This technique has met with partial success but has been limited by the difficulty of attaining the high temperatures required for reaction. The traditional carbon reduction technique also requires large sample sizes and a time-consuming degassing procedure, and is claimed to be unsatisfactory for alkali-bearing minerals. This is a result of the volatile alkali metals being oxidized by the evolved CO, which involves a large isotopic fractionation.

The laser-based carbon reduction technique of Sharp and O'Neil allows for reduced sample sizes of 1–3 mg or less, and because the heating is so rapid, analyses can be made much more quickly and cleanly than with either the conventional fluorination or carbon reduction method.

The carbon reduction method is based on the fact that all common oxides and silicates will be reduced in the presence of carbon, if sufficient temperatures are reached. For example, quartz and magnetite are reduced by the following reactions, respectively:

$$SiO_2 + 3\,C = SiC + 2\,CO, \text{ and}$$

$$Fe_3O_4 + 4\,C = 3\,Fe + 4\,CO.$$

Above 2400°C, all common oxides in the presence of graphite should be reduced to either elements or carbides. Temperatures of 2617°C (melting point of molybdenum) are easily achieved with the Nd-YAG laser equipment at the Geophysical Laboratory.

The extraction system developed by Sharp and O'Neil consists of a laser, a sample crucible, a reaction chamber and a CO-$CO_2$ converter (Fig. 3). A variable power, 18-watt maximum Nd-YAG laser ($\lambda = 1.064$ μm) with a 6X air-objective is used as a heating source. The focal length of this lens is 20 mm with a focused spot of ~10 μm. Although most minerals are transparent to radiation of this wavelength, graphite strongly absorbs the radiation and heats up. The admixed mineral is heated by conduction from the graphite powder. The reaction chamber containing the sample pellet is evacuated and degassed at 600°C for one hour. The sample is gently rastered under the focused laser beam until the sample pellet is entirely reacted. The evolved CO is collected on the cold finger as the reaction proceeds. The CO is then converted to $CO_2$, and the gas is fed to a sample tube for isotopic analysis.

Safety, rapidity, and small sample sizes are the primary benefits of the laser-based carbon reduction technique over conventional fluorination. Microvariations in the $\delta^{18}O$ of quartz veins, porphyro-

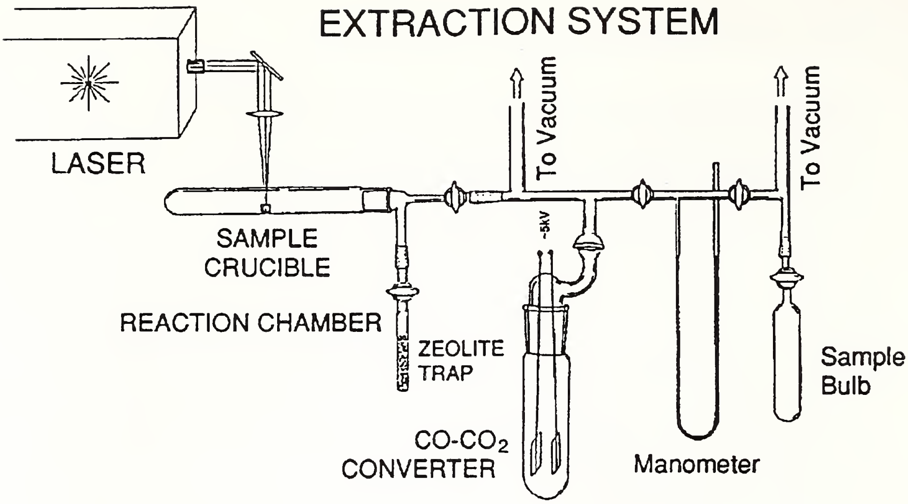



Fig. 3. Laser extraction system. The system consists of a Nd–YAG laser, a sample crucible, a reaction chamber with zeolite trap, and a CO–$CO_2$ converter. During reaction, the CO is collected on the zeolite trap, which is removed from the reaction chamber and placed onto the vacuum line. The CO is then desorbed and converted to $CO_2$ on the CO–$CO_2$ converter.

blasts, and phenocrysts can be measured with this new method. Unfortunately, not all minerals are amenable to the carbon reduction method at this time, but further investigations of the isotopic systematics involving the laser-based carbon reduction technique may lead to a better understanding of high-temperature, rapid kinetic processes that occur during laser heating.

### *Mineral Physics*

Geophysical Laboratory activity in mineral physics is centered around experimentation at high pressures and high temperatures; new developments have occurred primarily in studies of hydrogen and the discovery and characterization of hydrous and anhydrous magnesium silicates.

*Metallic hydrogen.* An exciting development this year was the high-pressure experiment performed by Ho-kwang Mao and Russell Hemley in which they observed a gradual increase in opacity in solid hydrogen as pressure was increased from 150 GPa* to about 250 GPa. Theory predicts that solid hydrogen in the molecular form $H_2$ will dissociate to form an atomically bonded, metallic solid at very high pressure (250–400 GPa). It has also been calculated that at somewhat lower pressure (below 200 GPa), intermediate transformations from the insulator state would occur, first forming

*100 Gigapascals = 1 megabar, or approximately one million times atmospheric pressure at sea level.

a semiconductor and then a conducting molecular metal. In addition, at about 180 GPa they observed that the intensity of the characteristic molecular hydrogen peak in the Raman spectrum was enhanced—a resonance effect indicating the presence of electronic transitions in the visible region of the spectrum. The resonance effect shifted to longer wavelengths with increasing pressure, indicating changes in the electronic structure of the hydrogen. (See p. 126.)

Mao and Hemley say that at pressures between 2.5 and 3.0 Gpa they have encountered indications, not yet conclusive, that the transition to the atomic metallic form may occur. At these higher pressures, the Raman resonant signal disappeared, suggesting that the molecules in the solid hydrogen may have dissociated, converting the material into an atomic solid. They add, however, that the high background readings at these pressures, as well as interfering signals from the diamonds themselves, make the evidence for atomic hydrogen inconclusive at present.

In 1979, Mao and Peter Bell became the first to observe the transition of hydrogen to the solid, crystalline form at room temperature, a phenomenon commencing at 5.7 GPa. Two years ago, Mao, Hemley, and colleagues exploited synchrotron x-radiation to perform the first x-ray diffraction studies of hydrogen at high pressure in a diamond-anvil cell.

Hydrogen is of special interest because an understanding of the nature of its bonding is fundamental to understanding bonding in all materials. (The metallic form of hydrogen at high pressure was first predicted in 1935. Subsequently, some predictions suggest that metallic hydrogen in the atomic form could be a high-temperature superconductor.) Observation of the intermediate transition is an important step toward understanding the predicted atomic transition.

*Synthesis and Characterization of New Silicate Phases at High Pressures and Temperatures.* Research associate Liang-chen Chen and staff members Ho-kwang Mao and and Russell Hemley have continued their work on the compression and polymorphism of $CaSiO_3$ at high pressures and temperatures. Previous experimental studies have determined high-pressure properties of magnesium and iron-magnesium silicates, but much less information is available on those of $CaSiO_3$ at upper and lower mantle conditions. One high-pressure modification of $CaSiO_3$ is already known to occur at about 3 GPa (walstromite–$CaSiO_3$ II), and a higher pressure phase (~46 GPa) is thought to be cubic perovskite. In the present study, $CaSiO_3$ II was observed to convert to a new non-quenchable phase ($CaSiO_3$ III) above 8 GPa that is stable to 11 GPa. This phase converts to walstromite-type $CaSiO_3$ II when quenched to ambient conditions. Experimental determination

of the density, structure, and elastic properties of $CaSiO_3$ III is essential in order to assess the possible role of this phase in the upper mantle.

Predoctoral fellow James Kubicki and Russell Hemley discovered spectroscopic evidence for a new high-pressure magnesium silicate phase. Experimental constraints on the mineralogy of the lower mantle have mainly been obtained from high-pressure phases that are quenchable to ambient pressure and temperature. A series of experiments have been started using the laser-heated, diamond-anvil cell and micro-Raman spectroscopy to investigate the possible existence of non-quenchable phases under lower mantle conditions. Micro-Raman spectroscopy was employed to probe the sample after melting and quenching at high pressure. With micro-Raman spectroscopy, it is possible to study any heterogeneities in the sample that may be induced by laser-heating. The in situ nature and spatial resolution of the technique are ideally suited for identification of small amounts of non-quenchable high-pressure phases.

The spectrum most probably arises from a previously unidentified phase that appears to be non-quenchable from high pressures. Also, it has been demonstrated that micro-Raman spectroscopy, used in combination with the laser-heated, diamond-anvil cell, is a useful technique for probing the possible existence of non-quenchable, high-pressure phases. Future work to analyze the structure of newly identified phases should be carried out with in situ, high-pressure x-ray diffraction and transmission electron microscopy techniques.

Senior postdoctoral fellow Yashiro Kudoh, Larry Finger, Robert Hazen, Charles Prewitt, and Masami Kanzaki of the University of Alberta initiated a single crystal x-ray diffraction study of a new hydrous magnesium silicate, phase E. Previously, four magnesium silicate phases had been identified in the system $MgO\text{-}SiO_2\text{-}H_2O$ at pressures between 10 and 18 GPa kbar and at temperatures from 600 to 1100°C. Among these, phase B is known to have a temperature-pressure stability field higher than the others, but its Mg/Si ratio is 3.0. In investigating phase relations in the system $MgO\text{-}SiO_2\text{-}H_2O$ up to 15 GPa and 1500°C using a uniaxial split-sphere multi-anvil apparatus, Kanzaki discovered a new phase that he denoted phase E. This hydrous silicate phase has Mg/Si less than 2, close to that of the mantle. The starting material was a stoichiometric mixture of high-purity $SiO_2$ and $2Mg(OH)_2$. The composition of phase E can be derived from a brucite starting point with a cell content of $Mg_3(OH)_6$. If a magnesium atom is removed, silicon atoms in tetrahedral coordination can be placed over this vacancy. The two possible reactions are

$$Mg(OH)_2 + Si^{4+} \rightarrow SiO_2 + Mg^{2+} + 2H^+,$$

which corresponds to a single Si per Mg removed, and

$$2Mg(OH)_2 + 2Si^{4+} \rightarrow MgSi_2O_4^{2+} + Mg^{2+} + 4H^+,$$

which results when two Si are involved. The measured composition corresponds to 1.73 Si atoms added for each Mg removed from the hypothesized starting position, which indicates that both mechanisms apply; however, the second one is more important. From the diffraction data, it is obvious that these substitutions result in short-range order. Although clusters of defects are expected, the size of the cluster does not result in diffuse scattering with appreciable intensity. Long-term x-ray photographs indicate the existence of diffuse maxima with the *a* axis seven times longer and the *c* axis doubled, as compared to the subcell.

*Optical Properties of Diamonds at Very High Stresses.* Russell Hemley and Ho-kwang Mao have examined new optical transitions in Type Ia diamonds at very high stresses.

The generation of ultrahigh pressures in the megabar range is now routine with the diamond-anvil, high-pressure cell. One of the important features of the diamond-cell arises from the transparency of the diamond anvils to large regions of the electromagnetic spectrum, permitting spectroscopic characterization of materials at high pressures using ultraviolet, visible, and infrared radiation. Type Ia diamonds are used in ultrahigh pressure studies owing to the presence of nitrogen platelets which may enhance their strength. The nitrogen impurities in these diamonds give rise to a variety of absorption and luminescence systems in the visible and ultraviolet at ambient pressures. In optical studies using the diamond-anvil cell, the absorption system at 3 eV in type Ia diamonds serves as an effective absorption edge, precluding most optical measurements at higher energies. Laser excitation in this region gives rise to a broad background fluorescence that can complicate optical measurements of samples within the cell. Further, the enhancement of this luminescence at very high pressure (above 200 GPa) can interfere with measurements of ruby fluorescence used for pressure determination.

Recently, Hemley and Mao performed a series of optical studies of hydrogen and a variety of materials compressed at pressures in the 200 GPa range. During the course of this work they discovered dramatic changes in the optical characteristics of the diamonds in the high-stress regions (tips) of the anvils. Documenting these effects is essential for further optical studies of materials at pressures above 200 GPa. In particular, this work is a prerequisite for optical characterization of the pressure-induced insulator-metal transition in hydrogen and other systems. In the present work, optical measurements were performed on anvils with tips 25–50 mm in diameter, culets of 300–500 mm, and bevel angles of 8–

10°. With increasing stress (corresponding to sample pressures above 200 GPa) a fluorescence peak appears at 2 eV. At very high pressures the signal dramatically increases. The peak tends to shift toward lower energies with higher energy excitation. Absorption extending throughout the visible region of the spectrum, with a broad peak at 2.4 eV, is also observed.

These changes in the fluorescence and absorption spectra of the diamonds are accompanied by new Raman bands (Fig. 4). Changes in the Raman spectra have been documented with samples consisting of hydrogen, neon, ruby, NaCl, and $SiO_2$. Although the relative wavenumbers of the bands are independent of laser excitation wavelength (indicative of Raman transitions), they are superimposed on a structured fluorescent background, which is especially strong with 488.0 and 514.5 nm excitation. In addition, the intensities of the Raman bands showed a large degree of resonance enhancement with decreasing wavelength (e.g., 647.1 to 476.5 nm). The bands were found to be reversible on releasing the stress, although the 590 $cm^{-1}$ peak can remain at low sample pressures (~30 GPa) before disappearing. The tips of the diamonds have been found to exhibit higher luminescence intensity upon unloading.

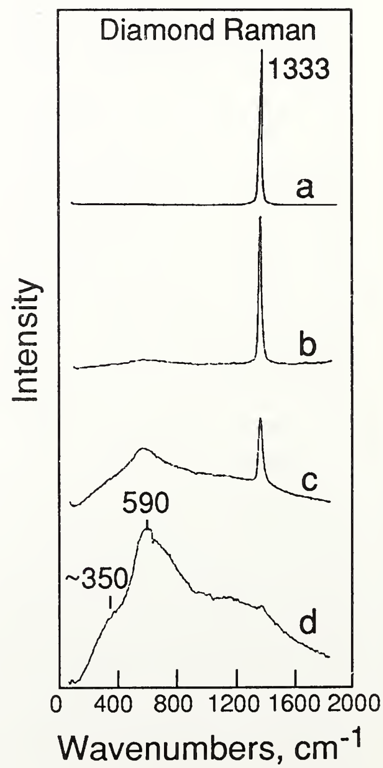



Fig. 4. Raman spectrum of a type Ia diamond anvil as a function of distance from a sample at ultrahigh pressure: *a*, 30μm. *b*, 20μm. *c*, 10μm. *d*, sample-diamond interface. The sample consisted of NaCl and ruby at a peak pressure of ~250 GPa.

The present experiments demonstrate that significant changes in the electronic properties of type Ia diamonds occur at stresses in the 200 GPa range. The luminescence enhancement may be due to pressure-induced electronic changes in deep level impurity centers. Alternatively, the new bands may be associated with actual changes in the diamond structure. There is a close similarity between the new Raman features and the one-phonon density of states of diamonds which has a broad peak centered at 600 $cm^{-1}$. Such a correlation would imply a breakdown in crystalline selection rules, resulting perhaps from growth of defects at the anvil tips or macroscopic flow of the diamond. Although a structural transformation in the diamond itself induced by non-hydrostatic stress also cannot be ruled out, Hemley and Mao's results indicate that such a transition must be reversible. Similar measurements carried out on different diamond types (type II, Ib, including synthetics) can be used to determine the extent to which the optical effects are associated with impurities or are intrinsic to diamond.

*Effect of Temperature and Pressure on $MgSiO_3$ Perovskite.* Ho-kwang Mao, Russell Hemley, research associates Jinfu Shu and Liang-chen Chen, postdoctoral fellow Andrew Jephcoat, Yan Wu of Lawrence Berkeley Laboratory, and William A. Bassett of Cornell University have studied the effect of pressure, temperature, and composition on the lattice parameters and density of $(Fe,Mg)SiO_3$-perovskites to 30 GPa.

Information on the physical properties (density, bulk modulus, and lattice parameters) of the $MgSiO_3$-perovskite as a function of pressure, temperature, and Fe-Mg composition is of fundamental importance for a realistic model of the lower mantle, and this work is complementary to the element partitioning studies by Fei, Mysen, and Mao mentioned previously. Although there is a growing body of data on these properties from high-pressure single-crystal and polycrystalline x-ray diffraction, from Brillouin scattering measurements and from theoretical calculations, little is known about the properties of perovskite at higher pressures. Indeed, the equation of state of the orthorhombic perovskite has not been studied above 13 GPa under hydrostatic pressure conditions. (Hydrostatic pressure is necessary for distinguishing the compressibility of individual lattice parameters.) Previous quasihydrostatic measurements on the elasticity of the perovskite were made at ambient conditions or at pressures far below the stability field of the perovskite, which could cause samples to behave abnormally. No measurements have yet been carried out at simultaneous high-pressure and high-temperature conditions. The effects of Fe/Mg ratio on the equation of state of the perovskite, which is crucial for the determination of the iron content in the mantle, also has not been studied experimentally or theoretically.

In summary, the differences in $K_0$ (bulk modulus) among various studies of $MgSiO_3$-perovskite are larger than the claimed uncertainty in each study, but are much smaller than those typically observed in various studies of other materials. It is also important to emphasize that although the extrapolated zero-pressure parameters are useful for comparisons with low-pressure data, they do not carry any specific significance in high-pressure experiments. Since the purpose of studying the $(Fe,Mg)SiO_3$ perovskite for solid-earth geophysics is to assess its role in the lower mantle, the more important parameters are the density and bulk modulus of perovskite with the appropriate composition above 20 GPa. These parameters were measured directly in the present study.

*Field and Observational Petrology*

Although much of the Laboratory's research is experimental in nature, it is extremely important that our research programs not lose sight of the importance of field studies or the insight that can be gained from analytical studies of important geological problems.

*Kaapvaal Spinel Peridotites: Evidence of Craton Origin.* F. R. Boyd is continuing his studies of continental cratons that have mantle roots extending to depths of at least 200 km; such cratonic lithosphere has a thickness that is two or more times that of oceanic plates. Cratonic lithosphere also differs from oceanic in composition: the garnet peridotites that are the principal components of the Kaapvaal lithosphere, southern Africa, have markedly lower Mg/Si, lower Ca/Al, and higher Mg/Fe than do residual oceanic peridotites, and their compositional relations are believed to be representative of other cratons. The origin of these differences in structure and composition between cratons and oceanic plates is an important chapter in earth history.

There are few constraints on the origin of craton roots other than their Archaean age. At least two scenarios seem possible. Cratonic nuclei might have developed at oceanic spreading centers and subsequently been underplated by peridotites having compositions similar to Kaapvaal garnet peridotites. If that origin occurred, peridotites now forming the shallow portions of craton roots should have composition typical of oceanic peridotites. Alternatively, the cratonic lithosphere in its entirety may be uniquely different in composition and origin from oceanic lithosphere. In that event, peridotites forming the top of a craton root would have compositions similar to the underlying garnet peridotites.

Evidence required to distinguish between these possible processes of craton development can be obtained by study of the compositional relations of the spinel-facies peridotites that occupy the upper

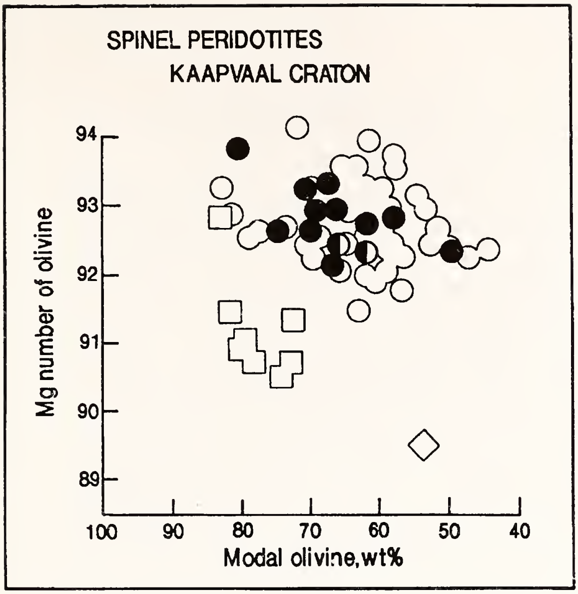



Fig. 5. Compositional data for Kaapvaal spinel peridotites (solid circles) and transitional rocks (half-solid circles) compared with data for low-temperature, Kaapvaal garnet peridotites (open circles), oceanic residues (open squares), and pyrolite (open diamond). Most of the spinel peridotites are from the Premier mine, but samples from Kimberley, Frank Smith, and Letseng are included.

portion of the craton lithosphere. Spinel peridotites are of widespread occurrence in xenolith suites of the Kaapvaal craton, having been collected at over a dozen localities in South Africa and Lesotho. Their proportions in individual xenolith suites vary widely from small to amounts approaching those of garnet peridotites. The relative abundance of spinel peridotites has led others to propose that they form a continuous layer at the top of the craton lithosphere, overlying garnet peridotites that are the principal rock type at greater depth.

Boyd recently showed that data for the Kaapvaal spinel peridotites superimposed on plots for low-temperature garnet peridotites and oceanic peridotites clearly overlap the garnet-facies rocks (Fig. 5). These data suggest a common origin for the Kaapvaal peridotites, whether of spinel or garnet facies. The compositional differences between these cratonic peridotites and oceanic residues make it appear unlikely that any large part of the Kaapvaal craton originated as an oceanic plate. Cratonic peridotites may have formed as buoyant residues of segregated ultramafic liquids at depths of 300–400 km. The circumstances in which these residues floated in a denser, more fertile, and largely crystalline mantle and coalesced to form proto-cratons are difficult to clarify. Underplating may have played a role in this process, however, and the spinel peridotites at the top of the cratonic lithosphere might be the oldest rocks in these ancient tectonic blocks.

*Fracture-Controlled Fluid Flow during Chlorite-Grade Metamorphism.* Douglas Rumble, Nicholas Oliver, and Thomas Hoering

have examined fracture-controlled fluid flow during chlorite-grade metamorphism at Waterville, Maine. A current controversy in studies of metamorphic rocks concerns the nature and extent of fluid flow during metamorphism. Some researchers have found fluid-rock ratios as high as 17.1 in bedded carbonate metasediments. Other workers point out, however, that if large ratios are characteristic of an entire metamorphic complex rather than merely pertain to specific acquifers, difficult questions arise about a feasible source for such vast amounts of fluid. Significant caveats have been issued regarding uncertainties in the magnitude of fluid-rock ratios measured with the reaction progress method. Resolving the controversy is important because of the ramifying effects the putative fluids would have on metamorphic belts. Among the effects that have been claimed are (1) regional alkali metasomatism, (2) regional stable isotope metasomatism, (3) advective heat transfer, and (4) removal of fluid reaction products, allowing devolatilization to proceed to completion.

Rumble and colleagues are addressing the controversy by testing the hypothesis of fluid flow in the Waterville-Augusta area, Maine. The region was chosen for study because it is here that the reaction progress method of estimating fluid-rock ratios was developed and widely applied. The rocks of the area are the focus of a debate about the magnitude of fluid-rock ratios. A practical advantage of the locality is that stratigraphic units strike perpendicular across metamorphic isograds from chlorite to sillimanite zones. Thus, it is possible to measure metasomatic changes caused by metamorphism with minimal ambiguity.

They have found evidence of fluid-rock interaction in the outcrops of the Waterville limestone along the east bank of the Kennebec River in Waterville. Analysis of calcite and dolomite for $\delta^{18}O$ and $\delta^{13}C$ shows that there are cryptic alteration halos around certain veins in which wall rock values have been depleted by 1–2‰ in $\delta^{18}O$ and by similar amounts in $\delta^{13}C$. The halos are termed "cryptic" because no mineralogical features have been recognized apart from proximity to veins.

Their results demonstrate that chlorite-grade limestones were penetrated by fluid-filled fractures during the peak-to-waning stages of metamorphism. Fluids infiltrated into wall rocks to a depth of at least 4 cm from vein walls. The fluid/rock ratios calculated from isotopic data for wall rock infiltration are approximately 3.0 by volume, some eight times greater than the largest ratios estimated previously, for intergranular infiltration at the same outcrop.

—*Charles T. Prewitt*

## *Structure and Properties of Magmatic Melts*

**by Bjørn Mysen**

The predominantly silicate materials of the Earth's crust and mantle may exist in molten form at the temperatures and pressures of the interior. Bodies of these magmatic melts may, upon cooling, crystallize to form igneous rocks, either beneath the surface or sometimes after eruption at the Earth's surface. In all cases the igneous rock-forming process is largely defined by certain physical and chemical properties of the melts.

In recent years, several of us at the Geophysical Laboratory have shown that these physical and chemical properties are strongly related to the structures of the melts. We believe that an understanding of melt structure as a function of pressure, temperature, and chemical composition offers a means for characterizing and predicting the properties required to describe igneous processes. By means of extensive experiments with carefully chosen, chemically simple systems, we have determined the principal building blocks of silicate melts and glasses. Our ultimate purpose has been to apply our structural results, both experimental and theoretical, quantitatively to natural magmatic liquids. (In addition, structural information on silicate melts and glasses is needed in the industrial application of glass products.)

The chemical and physical properties of a silicate melt system most important in characterizing rock-forming processes include its thermochemistry and liquidus phase relations, its characteristics of element partitioning between minerals and melts, and its transport properties (viscosity, diffusivity, and conductivity). These properties are governed by the nature of the chemical bonding. A principal goal in our experimental studies of melt structure is, therefore, to identify and characterize quantitatively the relationships between these properties and the characteristics of the bonding of the materials.*

### *Structural Information*

Network-forming cations (T) are those that occupy the center of tetrahedra with oxygen at the corners (Fig. 1). Oxygens shared

*In studying silicate melt structure, our main areas of interest are (1) network-modifying cations (alkali metals, alkaline earths, ferrous iron, and, sometimes, ferric iron) and network-forming cations ($Si^{4+}$, $Al^{3+}$, $Ti^{4+}$, $Fe^{3+}$, and $P^{5+}$), (2) aluminum, and the relationship between tetrahedrally coordinated $Al^{3+}$ and cations required for its electrical charge-balance, (3) ferric iron as a network-former and network-modifier, together with charge-balance considerations of tetrahedrally coordinated $Fe^{3+}$, and (4) other cations, principally titanium and phosphorous.

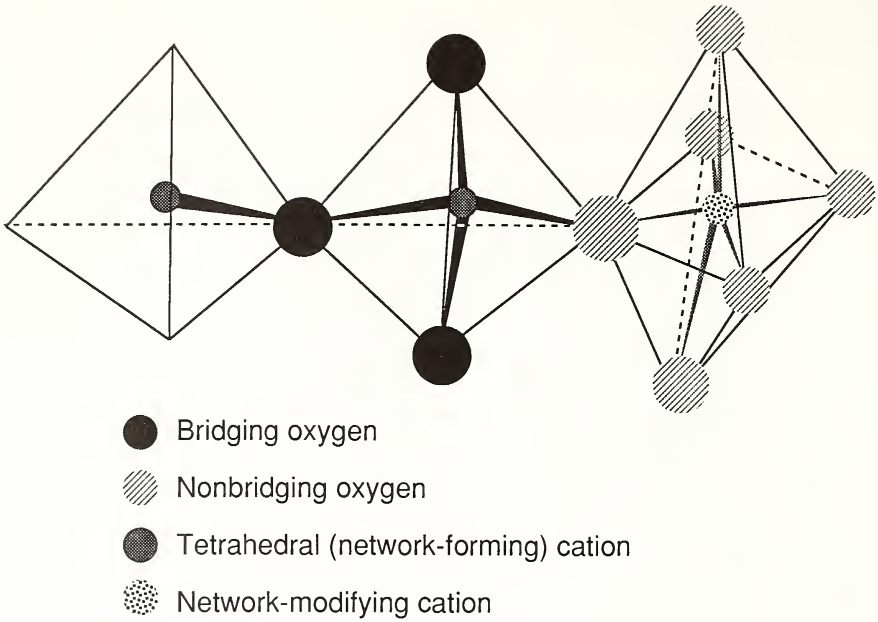



Fig. 1. Schematic representation of the structure around bridging and nonbridging oxygens.

by two neighboring tetrahedra are bridging (BO). Network-modifying cations (M) occupy the central location of oxygen polyhedra with more than four oxygens. Oxygens shared by a neighboring tetrahedron and a polyhedron with more than four oxygens are nonbridging (NBO).

The proportion of nonbridging (and bridging) oxygens in silicate melts describes its *degree of polymerization* and is defined as the number of nonbridging oxygens per tetrahedrally coordinated cations, or NBO/T for short. Silicate melts are composed of several types of coexisting structural units, each characterized by its NBO/T value (0, 1, 2, 3, or 4). In both simple and complex systems, the types and abundance of individual units are functions of the overall degree of polymerization of the melt, the types of T and M cations, temperature, and pressure. Experimental determination of silicate melt structure is aimed at quantitative understanding of how bulk chemistry, temperature, and pressure affect these structural features.

Experiments have been performed to temperatures of 1700°C in order to form melts of appropriate compositions in two-, three-, and four-component systems. Their structures were investigated with Raman, infrared, and Mössbauer spectroscopy. This structural information was then combined to describe the structures of complex magmatic liquids on the basis of their bulk chemical compositions. In doing so, we assume that the structural roles of individual cations in the simple systems are similar to those in the more complex natural systems. The first step in this procedure is to establish

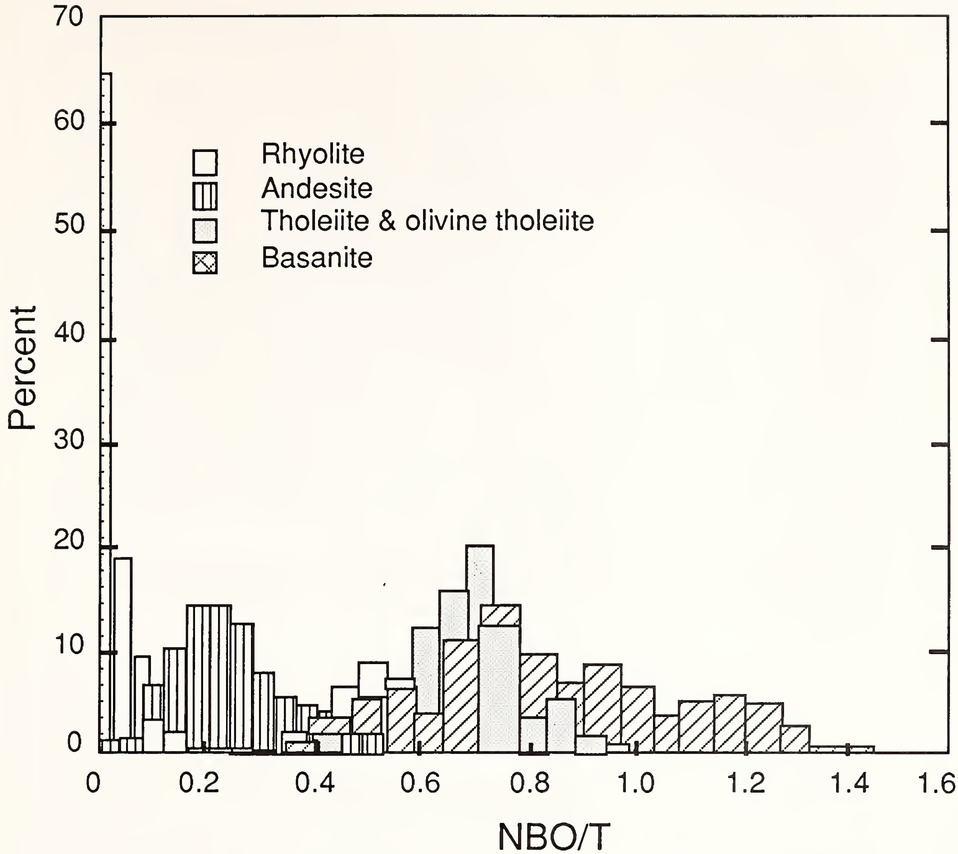



Fig. 2. Distribution of bulk melt NBO/T of magmatic liquids. The rock analyses were extracted from rock file RKNFSYS. Average values are: rhyolite, 0.031 ± 0.052; andesite, 0.247 ± 0.118; tholeiite and olivine tholeiite, 0.682 ± 0.147; basanite, 0.840 ± 0.254.

the proportions of tetrahedrally coordinated cations. The network-forming cations are silicon, aluminum, ferric iron, phosphorous, and titanium. The abundance of network-modifying cations in the melt is equal to their total abundance less that required to stabilize phosphate, aluminate, and ferrite complexes in the melt. The bulk melt NBO/T of a natural magmatic liquid now can be calculated.**

Distribution of NBO/T in melts of rhyolite, andesite, tholeiite, and basanite melt compositions is shown in Figure 2. The most

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**From the expression

$$\frac{\mathrm{NBO}}{\mathrm{T}} = \frac{1}{T}\sum_{i=1}^{i} nM_i^{n+},$$

where $M_i^{n+}$ is the proportion of network-modifying cation $i$ with electrical charge $n+$, and $T$ is the proportion of tetrahedrally coordinated cations.

common extrusive igneous rocks have NBO/T values between 0 and 1. The more felsic the igneous rock (i.e., the richer in silica, for example, as in rhyolite), the more polymerized it is (the greater the NBO/T). There are distinct maxima in the NBO/T distributions for each rock type, but the ranges of values spread quite widely.

As a result of the electrical charge-balancing requirements for $Al^{3+}$ and $Fe^{3+}$ in tetrahedral coordination, metal cations that exist as network-modifiers in simple metal oxide-silica systems, may not always be network-modifiers in natural magmatic liquids. For example, the alkali metal contents (Na, K, etc.) of most igneous extrusive rocks generally are so low that only in a fraction of the rhyolite and nephelinite will Na or K occur as network-modifiers (Fig. 3). In all but the most felsic rocks (rhyolite), magnesium is the most imortant network-modifier, followed by ferrous iron. In rhyolite-composition melts, the relative importance of ferrous iron and magnesium is reversed (Fig. 3).

The abundances of anionic structural units in natural magmatic liquids can be estimated from experimental data. The most

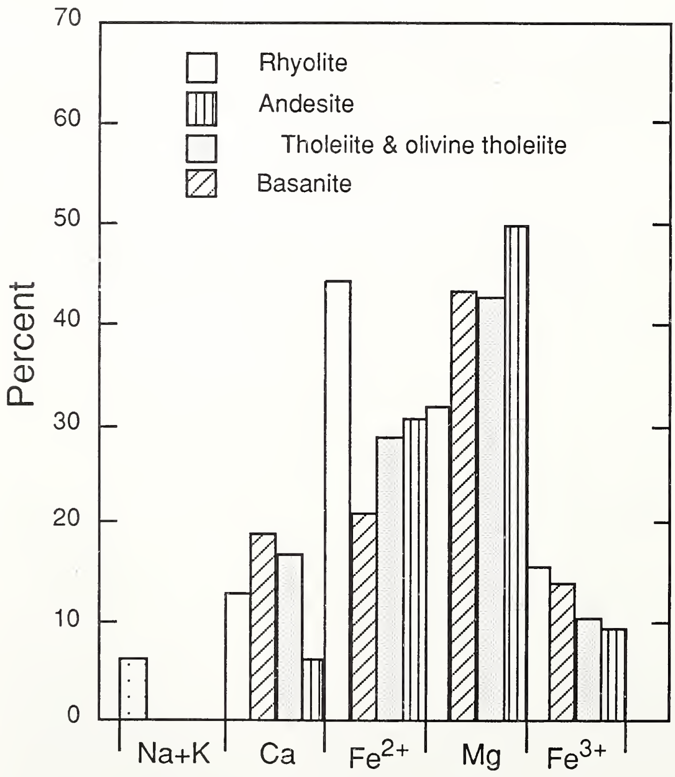


Fig. 3. Distribution of network-modifying cations in melts of major extrusive rock types.

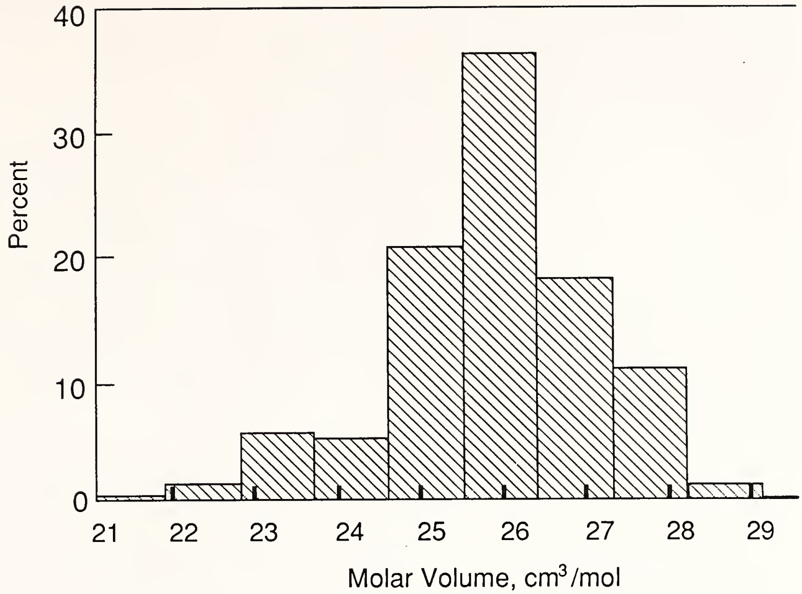


Fig. 4. Distribution of calculated molar volume ($cm^3/mol$) in melts of major extrusive rock types.

important structural units in most natural magmatic liquids are those with NBO/T values of 0 ($TO_2$) and 2 ($TO_3$). Compositions in the bulk melt NBO/T range between 0.3 and 0.4 (typically corresponding to andesite) are exceptions, where units with NBO/T = 1 ($T_2O_5$) may be more important; compositions with bulk NBO/T < 0.2 (corresponding to rhyolite and the most felsic andesite compositions) are also exceptions, where units with NBO/T = 2 are not present in the melt and the nonbridging oxygens occur only in units with 1 and 4 ($TO_4$) nonbridging oxygens per tetrahedron.

*Structure and Properties*

*Molar Volume.* The molar volume of magmatic liquids is a fundamentally important variable for characterization of the density and compressibility of the materials. Thus, processes of magma aggregation at the source of partial melting, and ascent and emplacement mechanisms of natural magma, can be understood only with information on this property. Molar volume varies widely as a function of magma composition (Fig. 4) and can be related to the structure of the liquid. A very simple positive linear correlation exists between molar volume, $V$, and the proportion of three-dimensional network units in the melt ($TO_2$) by the least-squares-fitted straight line

$$V = (16.33 \pm 0.05) + (11.72 \pm 0.07)X_{TO_2}.$$

In this expression, $X_{TO_2}$ represents the mol fraction of structural units with no nonbridging oxygens (fully polymerized). The proportions of $TO_3$ (NBO/T = 2) and $TO_4$ (NBO/T = 4) units vary inversely with $TO_2$. Thus, as expected, the molar volumes of natural magmatic liquids decrease systematically with increasing abundance of $TO_3$ and $TO_4$ units in the melts. No apparent correlation exists between molar volume and the abundance of $T_2O_5$ units in the magmatic liquids. Analogous linear relations exist between molar volume of $TO_2$ units in binary metal oxide-silica melts. It appears, therefore, that the proportion of three-dimensional network units is the principal structural control of the molar volume of natural magmatic liquids, and that the molar volume can be estimated provided that the $X_{TO_2}$ value is known. The more felsic the liquid the larger the molar volume.

*Viscosity.* Magma aggregation and ascent mechanisms in the mantle and crust of the Earth and terrestrial planets are controlled by the viscosity of the liquid. Melt viscosity is an important function of bulk composition, temperature, and pressure. It is necessary, therefore, to characterize the relationship between structure and viscosity in order to describe the viscous behavior of natural silicate liquids.

The distribution of activation energies of viscous flow ($E_\eta$) are shown in Figure 5. (The activation energy is that needed to rupture chemical bonds to form a flow unit and move the unit through adjoining melt during viscous flow.) The apparent bimodal distribution of activation energy values is at least partly due to the fact that, as for molar volumes, viscous properties of rhyolite melt tend to cluster in a group separated distinctly from other rock types, rhyolite having significantly greater viscosities and activation energies of viscous flow. At 1300°C, for example, the average melt viscosity ($\log_{10}\eta$, poises) of rhyolite is 4.8 ± 0.3, andesite 3.7 ± 0.5, tholeiite 2.2 ± 0.2, and basanite 1.7 ± 0.3.

There is a positive correlation between viscosity and NBO/T and between activation energy of viscous flow and NBO/T in natural magmatic liquids, although there is significant scatter in the data. Similar observations have been made for binary and ternary compositions, at least for bulk melt NBO/T = 1. It is very likely, however, that the scatter results from several additional factors that control the viscous behavior of multicomponent melts. These factors include the types and proportions of network-modifying cations and the types and proportions of charge-balancing cations for tetrahedrally coordinated $Al^{3+}$.

*Oxidation State of Iron.* Iron is the only major-element component of natural magmatic liquids that can exist in more than one oxidation state under natural conditions. An understanding of the

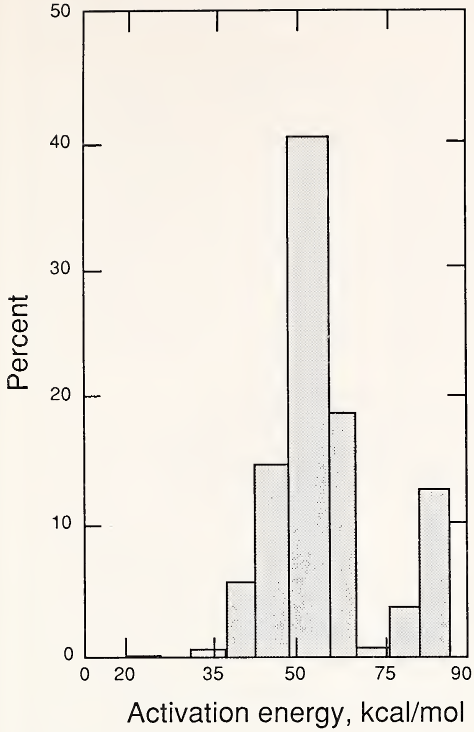


Fig. 5. Distribution of activation energy of viscous flow ($E_\eta$, kcal/mol) in melts of major extrusive rock types.

behavior of ferric ($Fe^{3+}$) and ferrous ($Fe^{2+}$) iron in magmatic systems is important for principally two reasons. (1) Whereas ferric iron can occur both as a network-former and a network-modifier in silicate liquids, ferrous iron is always a network-modifier. Consequently, the value of the redox ratio $Fe^{3+}/\Sigma Fe$ affects the structure (degree of polymerization) of the melt. Ferric iron is a network-former in highly oxidized melts ($Fe^{3+}/\Sigma Fe > 0.5$), whereas it is a network-modifier in more-reduced igneous materials. Any melt property that is affected by the degree of polymerization of the magmatic liquid is also, therefore, affected by the redox ratio of iron. (2) The temperature-oxygen fugacity histories of magmatic liquids are of central interest in igneous petrology. (Oxygen fugacity is the effective pressure of oxygen.) Such histories are in part recorded in the $Fe^{3+}/\Sigma Fe$ of the magma. Thus, knowledge and understanding of how $Fe^{3+}/\Sigma Fe$ is affected by bulk composition, temperature, pressure, and oxygen fugacity ($f_{O2}$) is necessary for a complete description of the petrogenesis of igneous rocks.

The $Fe^{3+}/\Sigma Fe$ of extrusive igneous rocks range from near 0 to 1.0. Under the assumption that the analyzed $Fe^{3+}/\Sigma Fe$ represents the $Fe^{3+}/\Sigma Fe$ of these materials prior to crystallization, the proportion of ferric iron in octahedral and tetrahedral coordination can be estimated. A breakdown of the results is shown in Table 1. It is evident that the more felsic the rock (and, therefore,

Table 1. Distribution of $Fe^{3+}/\Sigma Fe$ in groups of common igneous rocks.

| | | $Fe^{3+}/\Sigma Fe$ | | |
|---|---|---|---|---|
| Average | $Fe^{3+}/\Sigma Fe$* | <0.3 (%) | 0.3–0.5 (%) | >0.5 (%) |
| Rhyolite | 0.63 ± 0.25 | 13.9 | 17.2 | 68.9 |
| Dacite | 0.48 ± 0.20 | 23.3 | 43.1 | 33.6 |
| Andesite | 0.40 ± 0.07 | 28.9 | 49.7 | 21.5 |
| Tholeiite and olivine tholeiite | 0.29 ± 0.13 | 58.3 | 34.7 | 7.0 |
| Alkali basalt | 0.38 ± 0.19 | 36.6 | 40.1 | 23.3 |
| Nephelinite | 0.43 ± 0.16 | 23.3 | 43.1 | 33.6 |

*Average values for rock group. With $Fe^{3+}/\Sigma Fe > 0.5$, ferric iron is in tetrahedral coordination; with $Fe^{3+}/\Sigma Fe = 0.3–0.5$, both tetrahedral and octahedral ferric iron coexist in melts; and with $Fe^{3+}/\Sigma Fe < 0.3$, all ferric iron is in octahedral coordination. In octahedral coordination ferric iron is considered a network-modifier, whereas in tetrahedral coordination it is a network-former.

the more polymerized the melt), the more prevalent is tetrahedrally coordinated ferric iron. For rhyolite melt, for example, ferric iron is commonly in tetrahedral coordination, whereas for tholeiitic and more-basic melt, octahedrally coordinated ferric iron is common and $Fe^{3+}$ in tetrahedral coordination is unusual. An apparent consequence of this observation is that during fractional crystallization of basaltic liquid toward andesite or rhyolite, the residual liquids become more polymerized not only because of increasing silica (and, perhaps, alumina) content but also because the magma becomes more oxidized as it becomes more felsic.

The $Fe^{2+}/Fe^{3+}$ of magmatic liquids can be related to structural component, temperature, and oxygen fugacity. The structural components are those found to govern $Fe^{2+}/Fe^{3+}$ in binary and ternary systems. The expression

$$\ln\frac{Fe^{2+}}{Fe^{3+}} = a + \frac{10^4 b}{T} + c\ln f_{O_2} + d\left(\frac{Al}{Al+Si}\right) + e\left(\frac{Fe^{3+}}{Fe^{3+}+Si}\right) + \sum_{j=1}^{j} f_j\left(\frac{NBO}{T}\right)_j$$

can be used to describe the relationship between $Fe^{2+}/Fe^{3+}$, temperature, oxygen fugacity, and melt structure, where the coefficients have been determined by stepwise linear regression of several hundred experimentally determined values of $Fe^{2+}/Fe^{3+}$ as a function of structural components, temperature, and oxygen fugacity. The $f_j$ and $(NBO/T)_j$ are the regression coefficients and NBO/T values of the structural units associated with individual network-modifying cations, respectively.

Linear regression has been carried out with 460 experimental calibrations of $Fe^{3+}/\Sigma Fe$ in melt systems of varying chemical complexity. The equation shown above can be used as an oxygen

fugacity barometer. In Figure 6, the calculated $f_{O_2}$ values for the samples in the data set are compared with the measured values. The deviations of calculated oxygen fugacity values from those obtained experimentally are small. About 54% of the analyses are within $\pm 0.5$ log unit of oxygen fugacity and 85% within $\pm 1.0$ log unit of experimental values. About 95% fall within $\pm 1.5$ log units. This model, relating redox ratios of iron to temperature, oxygen fugacity, and melt structure, is an adequate description and can be used with confidence to calculate oxygen fugacity conditions of natural magmatic liquids at 1 bar.

*Element Partitioning.* The major, minor, and trace element concentrations in igneous rocks reflect their petrogenetic histories. All properties of magmatic systems can be related to the chemical compositions and the parameters that govern them. Thus, an understanding of the properties and processes that control element partitioning is critical for characterizing igneous processes. Experimental determination of element partitioning betwen minerals and melts with pressure, temperature, and bulk chemical composition pertinent to those during formation of magma is necessary in order to describe these histories on the basis of the elemental abundances. Unfortunately, despite the central importance of such experimental data, the data base is surprisingly small.

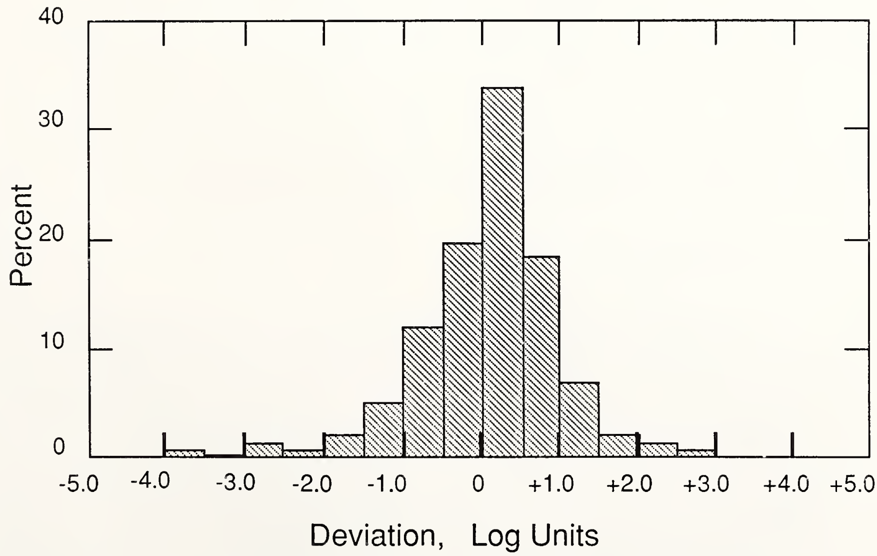


Fig. 6. Distribution of deviations of oxygen fugacity calculated with equation in text, opposite, from 490 experimental data points obtained from simple model systems and natural melt compositions. (Of the 490 experimental data points, 267 are from simple systems.)

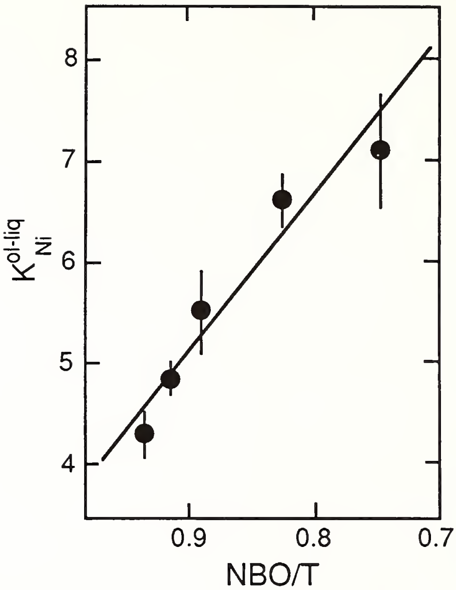


Fig. 7. Relation between partition coefficient $K_{Ni}^{ol\text{-}liq}$ for pure forsterite and liquid polymerization in the system diopside-nepheline-silica at 1 bar pressure and 1500°C. The correlation between property ($K$) and structure (NBO/T) is manifest.

From observations in natural rocks, it has been found that mineral-melt partitioning coefficients of the principal trace elements range by more than an order of magnitude as a function of bulk composition alone. Experiments have been conducted to determine how the structural variables in the melts are affected by composition and how these structural variables can be related to the trace element partition coefficients. In the case of element partitioning, as in other cases illustrated above, the degree of melt polymerization, NBO/T, is the principal factor (Fig. 7). At constant temperature and with the same bulk composition of the crystalline materials coexisting with melt, the values of most trace element partition coefficients increase rapidly with decreasing NBO/T. Melt polymerization alone is sufficient to account for the variations in trace element partition coefficients observed in igneous rocks.

*Concluding Remarks*

The principal facets of the structure of silicate melts and glasses pertinent to natural magmatic liquids have been identified experimentally. We have established, at least tentatively, the basic building blocks in magmatic liquids and can now estimate how their concentrations are affected by bulk chemical composition, at least at 1 bar pressure. Many of the most important properties of magmatic systems can be related quantitatively to the melt structures under near-surface pressure conditions.

A major challenge for the future stems from the premise that although near-surface processes represent the final stages of many igneous processes, the principal processes leading to these final stages occur at depth.

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*gie Instn. Washington, 1988–1989*, Geophysical Laboratory, Washington, D.C., 1989 (G. L. Paper 2150).

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Neil Irvine, standing beside a glacier crevasse in eastern Greenland, summer 1989. The glacier runs across the Skaergaard Intrusion, a formation long studied by Irvine and the site of a recently discovered new type of gold deposit, offering much scientific as well as economic interest.

# *Personnel*

*Research Staff*

Peter M. Bell[1]
Francis R. Boyd, Jr.
Felix Chayes, Petrologist Emeritus
Larry W. Finger
Marilyn L. Fogel
John D. Frantz
P. Edgar Hare
Robert M. Hazen
Russell J. Hemley
Thomas C. Hoering
T. Neil Irvine
Ho-kwang Mao
Bjørn O. Mysen
Charles T. Prewitt, Director
Douglas Rumble III
David Virgo
Hatten S. Yoder, Jr., Director Emeritus

*Keck Earth Sciences Research Scholar*

Gregory E. Muncill[2]

*Postdoctoral Fellows and Associates*

Ross J. Angel, Carnegie Fellow[3]
Liang-chen Chen, NSF Associate (Beijing University, China)[4]
Luis A. Cifuentes, Carnegie Corporation Fellow[5]
Donald D. Hickmott, Carnegie Corporation Fellow
Andrew P. Jephcoat, Wood Fellow[6]
Yasuhiro Kudoh, Carnegie Fellow[7]
Robert W. Luth, Carnegie Corporation Fellow[3]
Ming Sheng Peng, Geological Department of Central South Institute of Mining and Metallurgy, China
Nancy L. Ross, Carnegie Fellow[9]
Craig M. Schiffries, Carnegie Fellow
Zachary Sharp, Carnegie Fellow[4]
Jinfu Shu, Carnegie Associate
Peter Ulmer, Carnegie Corporation Fellow[3]
Ellen K. Wright, NSF Associate
Yi-gang Zhang, Carnegie Fellow[10]

*Predoctoral Fellows and Associates*

Constance Bertka, Carnegie Fellow

Yingwei Fei, Carnegie Fellow[10]
Matthew P. Hoch, Carnegie Fellow[8]
Nick Oliver, Monash University, Australia[11]
Kevin W. Mandernack, Carnegie Fellow[8]
Linda Stathoplos, Carnegie Fellow[4]
David J. Velinsky, Old Dominion University, Virginia

*Research Interns*

Brad P. Herman, St. Albans School, D.C.[12]
Virginia A. Mattingly, Georgetown Visitation Preparatory School, D.C.[12]
William A. Merrill, Georgetown Day High School, D.C.[12]

*Supporting Staff*

Andrew J. Antoszyk, Shop Foreman
Bobbie L. Brown, Instrument Maker[8]
Stephen D. Coley, Sr., Instrument Maker
Roy R. Dingus, Instrument Maker[13]
David J. George, Electronics Technician
Christos G. Hadidiacos, Electronics Engineer
Marjorie E. Imlay, Assistant to the Director
Lavonne Lela, Librarian
Harvey J. Lutz, Technician
Mabel B. Mattingly, Department Secretary
Mary M. Moore, Word Processor Operator—Receptionist
Lawrence B. Patrick, Maintenance Supervisor
David Ratliff, Jr., Maintenance Technician
Pedro J. Roa, Maintenance Technician
Susan A. Schmidt, Coordinating Secretary
John M. Straub, Business Manager
Mark A. Vergnetti, Instrument Maker[14]

*Visiting Investigators*

Ronald E. Cohen, Naval Research Laboratory
David H. Freeman, University of Maryland
Jaidong Ko, State University of New York, Stony Brook
James D. Kubicki, Yale University
Julie E. Kokis, George Washington University
Yali Su, University of Maryland
Bradley Tebo, Scripps Institution of Oceanography
Noreen C. Tuross, Smithsonian Institution
Donald J. Weidner, State University of New York, Stony Brook

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[1]Retired June 30, 1989
[2]To April 30, 1989
[3]To September 30, 1988
[4]To June 30, 1989
[5]To September 1, 1988
[6]To February 28, 1989
[7]From September 1, 1988
[8]From July 1, 1988
[9]To October 30, 1988
[10]From July 1, 1988 to June 30, 1989
[11]To June 1, 1989
[12]From June 1, 1989
[13]Transferred to DTM February 1989
[14]From April 1, 1989

# *Administrative Documents*

# Personnel

Members of the Departments are listed in the preceding sections.

*Special Appointments*

Roy J. Britten, Staff Member in Special Subject Area (Corona Del Mar, California)
Barbara McClintock, Distinguished Service Member in Special Subject Area (Cold Spring Harbor, New York)

*Office of Administration*
*1530 P Street, N.W.*
*Washington, DC 20005*

Lloyd Allen, Custodian
Ray Bowers, Editor and Publications Officer
Don A. Brooks, Custodian
Cady Canapp, Administrator for Personnel and Employee Benefits
Barbara A. Deal, Administrative Assistant
Jacqueline J. Green, Assistant to Administrator for Personnel and Employee Benefits
Michael Jenkins, Word Processing Technician
Sherman L. E. Johnson, Payroll Supervisor
Rickie Kanipe, Support Coordinator[1]
Anne Keatley, Director of Institutional and External Affairs[2]
John C. Lawrence, Controller
Ruthellen Madden, Financial Assistant[3]
Denise Marcone, Accountant[4]
Kristann Meares, Administrative Coordinator[5]
Diane Melick, Secretary to the President[6]
Patricia Parratt, Associate Editor
Catherine Piez, Accountant[7]
James Posey, Support Coordinator[8]
Arnold J. Pryor, Equal Opportunity Officer and Facilities and Services Supervisor
Christine Rogers, Financial Manager
Greg Silsbee, Grants and Contracts Administrator
Maxine F. Singer, President
Darlene Smith, Administrative Coordinator[9]
Susan Y. Vasquez, Assistant to the President
Yulonda White, Personnel and Benefits Records Coordinator

*Construction Project*

Gary Bors, Project Field Engineer[10]
Mary Lang, Secretary to Project Manager[11]
Murray Stewart, Project Manager

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[1]To March 15, 1989
[2]From August 1, 1988
[3]From January 1, 1989; Accounts Payable Assistant from July 25, 1988, to December 31, 1988
[4]To June 30, 1989; Financial Analyst from July 1, 1989
[5]From October 17, 1988, to March 10, 1989
[6]To June 30, 1989; Research Assistant from July 1, 1989
[7]To June 30, 1989; Systems Analyst from July 1, 1989
[8]From May 22, 1989, to June 21, 1989
[9]From March 20, 1989
[10]From December 1, 1988
[11]From January 3, 1989

# *Publications*

## Publications of the Institution

*Carnegie Institution of Washington Year Book 87*, viii + 227 pages, 52 illustrations, December 1988.

*Drosophila Guide: Introduction to the Genetics and Cytology of Drosophila melanogaster*, by M. Demerec and B. P. Kaufmann, 9th edition, with reading list and appendix by E. A. Carlson, 48 pages, 14 illustrations, reprinted April 1989.

*One Scientist's Journey*, Perspectives in Science booklet number 4, 40 pages, 25 illustrations, December 1988.

*CIW Newsletter*, issued in November 1988, March 1989, June 1989.

*Carnegie Institution of Washington*, informational booklet, 24 pages, 20 illustrations, August 1988, reprinted December 1988.

*Carnegie Evening 1989*, 12 pages, 16 illustrations, May 1989.

# *Report of the Executive Committee*

*To the Trustees of the Carnegie Institution of Washington*

In accordance with the provisions of the By-Laws, the Executive Committee submits this report to the Annual Meeting of the Board of Trustees.

During the fiscal year ending June 30, 1989, the Executive Committee held four meetings. Accounts of these meetings have been or will be mailed to each Trustee.

A full statement of the finances and work of the Institution for the fiscal year ended June 30, 1988, appears in the Institution's *Year Book 87*, a copy of which has been sent to each Trustee. An estimate of the Institution's expenditures in the fiscal year ending June 30, 1990, appears in the budget recommended by the Committee for approval by the Board of Trustees.

The terms of the following members of the Board expire on May 5, 1989:

Philip H. Abelson
Robert G. Goelet
Caryl P. Haskins
John D. Macomber
Howard A. Schneiderman
Charles H. Townes
Thomas N. Urban
Sidney J. Weinberg, Jr.

There are vacancies in the membership of the Executive Committee and the Nominating Committee caused by the resignation of Mr. William F. Kieschnick as a member of these Committees on January 17, 1989.

In addition, the terms of the Chairman of the Board, all Committee Chairmen, and the following members of Committees expire on May 5, 1989:

*Executive Committee*
William C. Greenough
Caryl P. Haskins
Gerald D. Laubach

*Finance Committee*
Sidney J. Weinberg, Jr.
William C. Greenough

*Employee Benefits Committee*
William C. Coleman, Jr.
Edward E. David, Jr.
Sandra M. Faber

*May 5, 1989*

Robert C. Seamans, Jr., *Chairman*

# *Abstract of Minutes*

*of the Ninety-Second Meeting of the Board of Trustees*

The Annual Meeting of the Board of Trustees was held in the Board Room of the Administration Building on Friday, May 5, 1989. The meeting was called to order by the Chairman, Richard E. Heckert.

The following Trustees were present: Philip H. Abelson, Lewis M. Branscomb, John Diebold, James D. Ebert, Sandra M. Faber, Robert G. Goelet, William T. Golden, William C. Greenough, Caryl P. Haskins, Richard E. Heckert, William R. Hewlett, Antonia Ax:son Johnson, Gerald D. Laubach, John D. Macomber, J. Irwin Miller, Richard S. Perkins, Thomas N. Urban, and Sidney J. Weinberg, Jr. Also present were Garrison Norton, Trustee Emeritus, Maxine F. Singer, President, Anne Keatley, Director of Institutional and External Affairs, John C. Lawrence, Controller, Susan Y. Vasquez, Assistant Secretary, and Marshall Hornblower, Counsel.

The Chairman reported the resignation of Robert M. Pennoyer. The Board accepted the resignation with regret.

The minutes of the Ninety-First Meeting were approved.

The reports of the Executive Committee, the Finance Committee, the Employee Benefits Committee, and the Auditing Committee were accepted.

Sections 1.1 and 1.2 of the By-Laws were amended. The amended language is given in the By-Laws printed on pages 189–194 of this Year Book.

On the recommendation of the Nominating Committee, James E. Burke and Sally K. Ride were elected members of the Board of Trustees, and the following were reelected for terms ending in 1992: Philip H. Abelson, Robert G. Goelet, Caryl P. Haskins, John D. Macomber, Howard A. Schneiderman, Charles H. Townes, Thomas N. Urban, and Sidney J. Weinberg, Jr.

Richard E. Heckert was elected Chairman of the Board for a term ending in 1992.

The following were elected for one-year terms: Robert C. Seamans, Jr., as Chairman of the Executive Committee; Sidney J. Weinberg, Jr., as Chairman of the Finance Committee; Philip H. Abelson, as Chairman of the Auditing Committee; and William T. Coleman, Jr., as Chairman of the Employee Benefits Committee. William T. Golden was appointed Chairman of the Nominating Committee for a one-year term.

Vacancies in the Standing Committees, with terms ending in 1992, were filled as follows: Philip H. Abelson, William C. Greenough, and Caryl P. Haskins were elected members of the Executive Committee; William C. Greenough and Sidney J. Weinberg, Jr., were elected members of the Finance Committee; Sidney J. Weinberg, Jr., was elected a member of

the Nominating Committee; and William T. Coleman, Jr., Edward E. David, Jr., and Sandra M. Faber were elected members of the Employee Benefits Committee. In addition, John Diebold was elected a member of the Auditing Committee for the unexpired term ending in 1990.

The annual report of the President was accepted.

To provide for the operation of the Institution for the fiscal year ending June 30, 1990, and upon recommendation of the Executive Committee, the sum of $23,760,000 was appropriated.

# *Financial Statements*

*for the year ended June 30, 1989*

## Carnegie Institution of Washington
## Ten-Year Financial Summary, 1980–1989
*(All figures are thousands of dollars; fiscal years ended June 30)*

| | 1989 | 1988 | 1987 | 1986 | 1985 | 1984 | 1983 | 1982 | 1981 | 1980 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Revenues** | | | | | | | | | | |
| Interest and dividends | $ 11,612 | $ 11,175 | $ 10,629 | $ 10,166 | $ 11,196 | $ 10,224 | $ 8,983 | $ 9,100 | $ 6,976 | $ 6,486 |
| Gifts and other | 708 | 273 | 955 | 543 | 1,277 | 996 | 1,338 | 1,342 | 561 | 313 |
| Restricted grants, expended | 6,059 | 5,924 | 4,673 | 5,595 | 5,198 | 4,308 | 4,476 | 4,587 | 3,912 | 2,613 |
| Total revenues | 18,379 | 17,372 | 16,257 | 16,304 | 17,671 | 15,528 | 14,797 | 15,029 | 11,449 | 9,412 |
| **Expenses** | | | | | | | | | | |
| Terrestrial Magnetism | 2,656 | 2,837 | 2,595 | 2,873 | 2,947 | 2,342 | 2,156 | 2,043 | 1,492 | 1,414 |
| The Observatories | 4,288 | 4,019 | 3,684 | 3,355 | 3,743 | 3,662 | 3,355 | 3,496 | 2,656 | 2,631 |
| Geophysical Laboratory | 2,932 | 2,989 | 2,511 | 2,399 | 2,391 | 2,204 | 2,096 | 2,434 | 1,724 | 1,595 |
| Embryology | 3,834 | 4,270 | 3,138 | 2,941 | 2,984 | 2,517 | 2,374 | 2,321 | 2,047 | 1,445 |
| Plant Biology | 2,155 | 1,846 | 1,985 | 1,828 | 1,763 | 1,402 | 1,467 | 1,168 | 1,024 | 913 |
| Research projects, etc. | 112 | 99 | 83 | 88 | 70 | 80 | 123 | 138 | 76 | 118 |
| Office of Administration | 1,304 | 1,204 | 1,199 | 1,277 | 1,242 | 1,197 | 1,099 | 1,073 | 941 | 791 |
| General publications | 151 | 174 | 155 | 137 | 63 | 80 | 67 | 76 | 91 | 66 |
| Professional fees, insurance, taxes | 637 | 424 | 533 | 271 | 208 | 327 | 311 | 264 | 231 | 199 |
| Retiree health insurance | 274 | 252 | 213 | 211 | 202 | 203 | 156 | 190 | 192 | 139 |
| Investment services | 686 | 699 | 736 | 690 | 389 | 411 | 395 | 385 | 342 | 278 |
| Total expenses | 19,029 | 18,813 | 16,832 | 16,070 | 16,002 | 14,425 | 13,599 | 13,588 | 10,816 | 9,589 |
| Excess (deficiency) of revenues over expenses before capital changes | $ (650) | $ (1,441) | $ (575) | $ 234 | $ 1,669 | $ 1,103 | $ 1,198 | $ 1,441 | $ 633 | $ (177) |
| Net realized and unrealized gain (loss) on investments | $ 16,969 | $ (6,904) | $ 17,754 | $ 45,731 | $ 26,142 | $ (11,546) | $ 39,410 | $ (4,764) | $ 6,711 | $ 7,430 |
| Market value of investments | $223,032 | $211,130 | $227,734 | $202,982 | $153,210 | $130,805 | $137,859 | $ 95,759 | $101,464 | $ 94,359 |

## CONTRIBUTIONS, GIFTS, AND GRANTS FOR THE YEAR ENDED JUNE 30, 1989

Philip H. Abelson
Jagannadham Akella
American Association for the Advancement of Science
American Astronomical Society
American Cancer Society
American Society for Microbiology
Bruce N. Ames
Philip Anderson
Matthew and Katherine Andrews[1]
ARCO Foundation
Paul A. Armond, Jr.
Frank B. Armstrong
Robert B. Arvidson
Toshi Asada
Liselotte Beach
David F. and Helen B. Bell
William L. Belser
Dorothea Bennett
Jack Bennett
Marian Beremand
Claire M. Berg
Douglas Berg
Judith Berman
L. Elizabeth and Giuseppe Bertani[2]
Albert P. Blair
Jef Boeke
Ellis T. and Elaine Bolton
John J. and Emma Bonica
E. Roger and Etta K. Boothroyd
Bent G. Boving
Montgomery S. and Joanne Bradley
The Branscomb Family Foundation
Gerald Braver
Robin Brett
Bristol-Myers Fund, Inc.
Lisa D. Brooks
Donald D. Brown
James H. and Susan E. Brown[1]
Jeanette Brown
Linda Brown
William L. Brown
Peter Bruns
Rosemary and David Buden
Allan B. Burdick
Patricia V. Burke
Charles R. Burnham
Mary C. Buynitzky
Breck Byers
John A. R. Caldwell
California Institute of Technology
Joseph Calvo
Allan M. Campbell
Malcolm John Casadaban
James F. Case
The Jane Coffin Childs Memorial Fund
J. Douglas Caston
D. G. Catcheside
B. Wesley Catlin
Kalpana Chakraburtty
Martin Chalfie
Vicki L. Chandler
Arthur Chovnick
Charles Chu
Robin Ciardullo
Alvin J. Clark
Arnold and Constance Clark
Edward H. Coe, Jr.
Stanley N. Cohen
William T. Coleman, Jr.
CPD HUD staff of Philadelphia[1]
Jean Cockrell Cowie
Carole L. Cramer
Harriet B. Creighton
John R. Cronin
R. H. Crozier
Gary S. DaCosta
John F. Dallas
Howard Clark Dalton
Patricia Daugherty
Edward E. David, Jr.
Edwin A. Davis
I. B. Dawid
Robert L. DeHaan
Louis E. DeLanney
Alison DeLong and John Sedivy
David M. DeMarini
Rob Denell
John Diebold
Stephen R. Dlouhy
Edward O. Dodson
Bruce R. Doe
A. H. Doermann
E. J. Dollinger
William R. Duryee
Donald N. Duvick
Mark and Eva Dworkin
James D. and Alma C. Ebert
Harrison Echols
Joel Eisenberg
Georgia C. Eizenga
Herbert and Marianne Eleuterio
Sarah C. R. Elgin
Donald L. Elthon
Carol Enderlin
Frank C. Erk
Exxon Education Foundation
David Featherston
Gerald R. Fink

*(continued)*

## CONTRIBUTIONS, GIFTS, AND GRANTS FOR THE YEAR ENDED JUNE 30, 1989 (continued)

Dorothy Ruth Fischer
Michael Fleischer
Walter S. Flory, Jr.
Seymour Fogel
Robert G. Fowler
Thomas D. Fox
Naomi C. Franklin
Robert Fuerst
Toshio Fukasawa
Catherine P. Fussell
Joseph Gall
Sumiko Gamo
Ann K. Ganesan
Gabriel J. Gasic
Ronald and Carol Gibbs[1]
Norman H. Giles
Christopher B. Gillies
Bentley Glass
Barry Glickman
Robert G. Goelet
Edward Goldberg
The Golden Family Foundation
Timothy and Mary Helen Goldsmith
Major M. Goodman
Richard H. Goodwin
Annamaria Torriani Gorini
Joseph S. Gots
Michael and Susan Gottesman
Govindjee
R. S. Gowe
William C. Greenough
Norio Gunge
William G. Hagar, III
Olli Halkka
Linda M. Hall
Richard Hallberg
Garrett and Jane S. Hardin
Philip D. Harriman
Pembroke J. Hart
William K. Hart
Philip and Zlata Hartman
Caryl P. and Edna Haskins
D. C. Hawthorne
Ulrich Heber
Richard E. Heckert
H. Lawrence Helfer[4]
Alfred D. Hershey
William R. Hewlett
William M. Hiesey
Walter E. Hill
Hoechst Celanese Corporation
Stanton F. Hoegerman
Jeanette J. A. Holden
Norman Horowitz
H. Robert Horvitz
Satoshi Hoshina
Magda G. Hotchkiss
Rollin D. Hotchkiss
Martha M. Howe
Howard Hughes Medical Institute
Incorporated Research Institutions for Seismology
F. Earl Ingerson
John B. Irwin
Sadao Ishiwa
Philip T. Ives
J. I. Foundation, Inc.
The George F. Jewett, Jr. 1965 Trust
The Johns Hopkins University
Roger C. Johnsen
Antonia Ax:son Johnson
Paul and Doris J. Johnson
Stephen A. Johnston
Burke H. Judd
Hiroaki Kagawa
Louis M. and Sally B. Kaplan Foundation
W. M. Keck Foundation
MacKenzie Keith
Albert Kelner
Sirkka Keranen
Kenneth K. Kidd
Don Killebrew
James C. King
Karla Kirkegaard
Anita Klein
Irwin R. Konigsberg
David C. Koo
Daniel Koshland, Jr.
Olavi Kouvo
Robert W. Krauss
Robert N. Kreidler
Raju Kucherlapati
Ikuo Kushiro
Ann M. Lacy
Charles D. Laird
Otto C. Landman
Robert L. Last
Gerald D. Laubach
Faith and Arthur LaVelle
A. H. Lawrence
Joshua Lederberg
Harold H. Lee
Robert W. Lee
Peggy Lemaux
Howard M. Lenhoff
Jules M. Lerner
Leukemia Society of America
Robert W. Levis, Jr.
Harland F. Lewis

*(continued)*

## Contributions, Gifts, and Grants for the Year Ended June 30, 1989 (continued)

Susan E. Lewis
Steven Li
Margaret Lieb
Susan W. Liebman
Johng K. Lim
Charles and Elizabeth Little
John and Estelle Little[1]
Felix J. Lockman
Edith C. London[3]
Eric Long
Susan T. Lovett
Thomas E. Lovejoy
Peter Luykx
John D. & Catherine T. MacArthur Foundation
John D. Macomber
Dina Mandoli
Arthur P. Mange
George Mannanal
Winston M. Manning
Lucille P. Markey Charitable Trust
Gregory Martin
Barbara and Chester B. Martin, Jr.
Georgiana May
Robert H. McCallister
Barbara McClintock
Sheila McCormick
Norman E. Melechen
The Andrew W. Mellon Foundation
Corinne A. Michels
Roger and Marianne Milkman
Gifford Miller
Mineralogical Society of America
James Mohler
Ambrose Monell Foundation
Monsanto Company
John A. and Betty C. Moore
Ray Moree
Rosalind Morris
Mary Lee Morrison
Gisela Mosig
John P. Mottinger
Norio Murata
Michael Murray
Jack E. Myers
Ferez S. Nallaseth
M. E. and J. B. Nasrallah
DeLill Nasser
National Academy of Sciences
Oliver E. Nelson, Jr.
Howard B. Newcombe
Lester J. Newman
Dorothy Newmeyer
Vivian Ngan
Robert A. Nilan
Darwin Norby
Garrison Norton
Kevin O'Hare
Yoshikazu Ohashi
Tokindo S. Okada
John C. Osterman
Ray D. Owen
University of Oxford
David C. Page
Kenneth Paigen
Karen Palter
Mary Lou Pardue
P. Pechan
Patricia N. H. Peebles-Ttee
Joseph G. Pelliccia
Robert M. Pennoyer
Richard S. Perkins
Peter A. Peterson
T. Peterson
Thomas Petes
Pfizer Inc.
Ronald L. Phillips
Jennifer L. Pinkham
Leonie K. Piternick
Daniel Pomp
Richard S. Preisler
Hope H. Punnett
Calvin O. Qualset
Elizabeth M. Ramsey, M.D., and Hans A. Klagsbrunn
Peter H. and Tamra Raven
Sheldon and Elizabeth Reed
Ron and Judy Roan Reeder
David J. Remondini
Charles M. Rick, Jr.
Hans Ris
John D. Rockefeller Foundation
Raymond L. Rodriguez
Robert G. Roeder
Mikeal L. Roose
Ann M. Rose
Walter C. Rothenbuhler
Rodney and Josie Rothstein
Irwin Rubenstein
Vera C. Rubin
Carole A. Sack
Ruth Sager
William and Margaret Samples[1]
Bonnie Sampsell
Allan Sandage
Sandoz Crop Protection Corporation
Debra Saxe
Ruth Schairer
Maarten and Corrie Schmidt
Matthew Scott
*(continued)*

## Contributions, Gifts, and Grants for the Year Ended June 30, 1989 (continued)

Robert C. Seamans, Jr.
E. R. Sears
James and Lisa Seeb
Martin G. Seitz
Richard F. Shaw
Nobu Shimizu
Edwin M. Shook
Eli C. Siegel
A. C. Sigleo
Willys K. Silvers
Maxine F. Singer
Ronald Singer
Rudolph J. and Anna Marie Skalka
Alfred P. Sloan Foundation
Elizabeth H. Smith
Harold H. Smith
P. Dennis Smith
Marlene Snyder
Alexander Sokoloff
C. Griffin and Allan Spradling
G. F. Sprague
Frank and Ruth Stanton Fund
Philip M. Stern Family Fund
Harry T. Stinson
Kevin Struhl
Roger D. Sumner
Millard Susman
Ian Sussex
Karen VanWinkle Swift
Paul Szauter
J. Herbert Taylor
The Teagle Foundation, Inc.
Heinz Tiedemann
Y. C. Ting
Laurie Tompkins
Charles H. Townes
J. Ives Townsend
Peter M. Tuft
Delta Uphoff
Thomas N. Urban
Neltje W. Van de Velde
N. Van Schaik
Larry N. Vanderhoef
David Wagner
Robert P. Wagner
Lillian Wainwright
Virginia Walbot
Virginia K. Walker
Bruce Wallace
Warner Communications, Inc.
Ellen C. Weaver
Steven Weaver
Sidney J. Weinberg, Jr. Foundation
J. A. Weir
The Weizmann Institute
Susan R. Wessler
Helen Hay Whitney Foundation
D. G. Whittingham
Dorothea Widmayer
Harry Winston Foundation, Inc.
Ulrike Wintersberger
Evelyn M. Witkin
Frederick T. Wolf
James E. Womack
Elizabeth A. Wood[3]
Chao-Ting Wu
Kenzo Yagi
Hideo Yamagishi
Armon F. Yanders
Charles Yanofsky
Ronald E. Yasbin
Violet K. Young
Bertram Zaslow[3]
Elizabeth Anne Zimmer

[1]In memory of Mr. Eric T. Crawford
[2]In memory of Dr. M. Demerec
[3]In memory of Dr. Gabrielle Donnay
[4]In memory of Dr. Richard B. T. Roberts

1801 K Street, N.W.
Washington, DC 20006

Telephone 202 833 7932

**Price Waterhouse**

## Report of Independent Accountants

September 6, 1989

To the Auditing Committee of the
Carnegie Institution of Washington

In our opinion, the accompanying statements of assets, liabilities, and fund balances and the related statements of revenues, expenses, and changes in fund balances present fairly, in all material respects, the financial position of the Carnegie Institution of Washington at June 30, 1989 and 1988, and the results of its operations and the changes in its fund balances for the years then ended, in conformity with generally accepted accounting principles. These financial statements are the responsibility of the Institution's management; our responsibility is to express an opinion on these financial statements based on our audits. We conducted our audits of these statements in accordance with generally accepted auditing standards which require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements, assessing the accounting principles used and significant estimates made by management, and evaluating the overall financial statement presentation. We believe that our audits provide a reasonable basis for the opinion expressed above.

Our audits were made for the purpose of forming an opinion on the basic financial statements taken as a whole. The supporting schedules 1 through 4 are presented for purposes of additional analysis and are not a required part of the basic financial statements. Such information has been subjected to the auditing procedures applied in the audit of the basic financial statements and, in our opinion, is fairly stated in all material respects in relation to the basic financial statements taken as a whole.

Price Waterhouse

## Statements of Assets, Liabilities, and Fund Balances
## June 30, 1989 and 1988

| | 1989 | 1988 |
|---|---|---|
| **Assets** | | |
| Cash and cash equivalents | $ 1,990,006 | $ 207,788 |
| Grants receivable | 805,327 | 754,405 |
| Accrued interest and dividends | 1,916,315 | 1,813,711 |
| Advances and accounts receivable | 222,617 | 60,464 |
| | 4,934,265 | 2,836,368 |
| Investments* (market) | | |
| Temporary | 14,664,000 | 29,050,944 |
| Fixed income—long term | 78,584,468 | 60,212,485 |
| Common stock | 129,084,983 | 121,149,825 |
| Other | 698,857 | 717,054 |
| | 223,032,308 | 211,130,308 |
| Plant | | |
| Land | 1,009,851 | 1,009,851 |
| Buildings | 5,153,840 | 4,987,495 |
| Equipment | 8,757,987 | 8,757,987 |
| Plant in service | 14,921,678 | 14,755,333 |
| Buildings under construction | 3,470,042 | 711,332 |
| | 18,391,720 | 15,466,665 |
| Total assets | $246,358,293 | $229,433,341 |
| **Liabilities and Fund Balances** | | |
| Liabilities | | |
| Accounts payable and accrued expenses | $ 1,833,901 | $ 1,370,500 |
| Deferred grant income | 2,823,180 | 2,846,684 |
| Total liabilities | 4,657,081 | 4,217,184 |
| Fund balances | 241,701,212 | 225,216,157 |
| Total liabilities and fund balances | $246,358,293 | $229,433,341 |

*Approximate cost on June 30, 1989: $190,208,110; June 30, 1988: $190,023,848

The accompanying notes are an integral part of these statements.

## STATEMENTS OF REVENUES, EXPENSES, AND CHANGES IN FUND BALANCES FOR THE YEARS ENDED JUNE 30, 1989 AND 1988

| | Year Ended June 30 | |
|---|---|---|
| | 1989 | 1988* |
| **Revenues** | | |
| Interest and dividends | $ 11,612,310 | $ 11,175,186 |
| Grants | | |
| Federal | 3,340,501 | 3,538,241 |
| Private | 2,717,590 | 2,386,222 |
| Gifts and other revenues | 708,425 | 272,722 |
| Total revenues | 18,378,826 | 17,372,371 |
| **Expenses** | | |
| Personnel and related | 10,810,339 | 10,127,678 |
| Equipment | 1,840,166 | 2,622,325 |
| General | 6,378,598 | 6,063,661 |
| Total expenses | 19,029,103 | 18,813,664 |
| Deficiency of revenues over expenses before capital changes | (650,277) | (1,441,293) |
| **Capital changes** | | |
| Realized net gain on investments | 5,251,249 | 11,062,784 |
| Unrealized gain (loss) on investments | 11,717,738 | (17,967,280) |
| Land, buildings, and equipment capitalized | 166,345 | 648,522 |
| Total capital changes | 17,135,332 | (6,255,974) |
| Excess (deficiency) of revenues and capital changes over expenses | 16,485,055 | (7,697,267) |
| Fund balances, beginning of year | 225,216,157 | 232,913,424 |
| Fund balances, end of year | $241,701,212 | $225,216,157 |

*Restated for comparative purposes.

The accompanying notes are an integral part of these statements.

## Notes to the Financial Statements
## June 30, 1989

*Note 1. Significant Accounting Policies*

The financial statements of the Institution are prepared on the accrual basis of accounting.

The Institution capitalizes expenditures for land, buildings, telescopes and other significant equipment, and construction projects in progress. Expenditures for other equipment are charged to current operations as incurred, and the cost of such other equipment is not capitalized. The Institution follows the policy of not depreciating its buildings, telescopes, and other significant equipment.

In connection with a building project currently under construction, the Institution has appropriated up to approximately $19.5 million in construction costs.

*Note 2. Employee Benefit Plans*

The Institution has a noncontributory, money-purchase retirement plan in which all United States personnel are eligible to participate. Until March 31, 1989, the Plan was funded in a trust managed by the Institution. Beginning April 1, 1989, the Plan is funded through individually owned annuities issued by Teachers' Insurance and Annuity Association (TIAA) and College Retirement Equities Fund (CREF). There are no unfunded past service costs. The total contributions made by the Institution were $1,133,179 in 1989 and $1,032,597 in 1988. After one year's participation, an individual's benefits are fully vested.

The Institution provides health insurance for retired employees. Most of the Institution's United States employees may become eligible for those benefits at retirement. The cost of retiree health insurance benefits is recognized as an expense as costs are incurred. For 1989 and 1988, those costs were $273,954 and $252,281, respectively.

*Note 3. Restricted Grants*

Restricted grants are funds received from foundations, individuals, and federal agencies in support of scientific research and educational programs. The Institution follows the policy of reporting revenues only to the extent that reimbursable expenditures are incurred. Reimbursement is based upon provisional rates which are subject to subsequent audit and potential downward adjustment. The Restricted Grants Statement (Schedule 3) shows all of the current grants.

*Note 4. Income Taxes*

The Institution is exempt from federal income tax under Section 501(c)(3) of the Internal Revenue Code. Accordingly, no provision for income taxes is reflected in the accompanying financial statements. The Institution is also an educational institution within the meaning of Section 170(b)(1)(A)(ii) of the Code. The Internal Revenue Service has classified the Institution as other than a private foundation, as defined in Section 509(a) of the Code.

*Note 5. Other Investments*

In order to assist in the relocation of certain key scientific staff, the Institution makes loans secured by real estate to these employees at below market interest rates. At June 30, 1989 and 1988, their outstanding value was $698,857 and $717,054, respectively.

SCHEDULE 1

## SCHEDULE OF EXPENSES BY DEPARTMENT FOR THE YEARS ENDED JUNE 30, 1989 AND 1988

| | 1989 | | | | 1988 |
|---|---|---|---|---|---|
| | Endowment and Special | Restricted Grants: Federal | Restricted Grants: Private | Total Expenses | Total Expenses |
| Education and scientific research expenses | | | | | |
| Terrestrial Magnetism | $ 2,106,606 | $ 421,495 | $ 127,488 | $ 2,655,589 | $ 2,836,735 |
| The Observatories | 3,171,752 | 303,970 | 812,637 | 4,288,359 | 4,019,002 |
| Geophysical Laboratory | 2,139,473 | 552,796 | 239,767 | 2,932,036 | 2,988,828 |
| Embryology | 1,092,522 | 1,656,728 | 1,084,845 | 3,834,095 | 4,270,445 |
| Plant Biology | 1,325,136 | 405,512 | 423,967 | 2,154,615 | 1,846,311 |
| Research projects, etc. | 83,355 | ... | 28,886 | 112,241 | 98,993 |
| Total | 9,918,844 | 3,340,501 | 2,717,590 | 15,976,935 | 16,060,314 |
| Administrative and general expenses | | | | | |
| Office of Administration | 1,304,240 | ... | ... | 1,304,240 | 1,204,266 |
| General publications | 151,103 | ... | ... | 151,103 | 173,908 |
| Professional fees, insurance, taxes | 636,529 | ... | ... | 636,529 | 423,594 |
| Retiree health insurance | 273,954 | ... | ... | 273,954 | 252,281 |
| Investment services | 686,342 | ... | ... | 686,342 | 699,301 |
| Total | 3,052,168 | ... | ... | 3,052,168 | 2,753,350 |
| Total expenses | $12,971,012 | $ 3,340,501 | $ 2,717,590 | $19,029,103 | $18,813,664 |

The accompanying notes are an integral part of these schedules.



CARNEGIE INSTITUTION OF WASHINGTON
FINANCIAL STATEMENTS

Schedule 2

## Changes in Fund Balances for the Year Ended June 30, 1989

| | Balance July 1, 1988 | Investment, Grant, and Other Income | Endowment and Special Gifts | Total Net Realized and Unrealized Capital Gains | Expenses | Other | Balance June 30, 1989 |
|---|---|---|---|---|---|---|---|
| Endowment Funds | | | | | | | |
| Andrew Carnegie | $149,214,274 | ... | ... | $12,819,738 | ... | ... | $162,034,012 |
| Sibyl and Wm. T. Golden | 71,326 | ... | $ 50,500 | 6,129 | ... | $285,600 | 413,555 |
| Anonymous gifts | 4,064,133 | ... | ... | 349,204 | ... | ... | 4,413,337 |
| Mellon Matching | 2,500,697 | ... | ... | 214,868 | ... | (226,300) | 2,489,265 |
| Astronomy Matching | 2,596,175 | ... | ... | 223,072 | ... | ... | 2,819,247 |
| Unrestricted Capital Funds | | | | | | | |
| Carnegie Corporation | 41,997,963 | ... | ... | 2,539,858 | ... | (804,973) | 43,732,848 |
| Carnegie Futures | 1,198,765 | ... | 139,313 | 103,002 | ... | (59,300) | 1,381,780 |
| Vannevar Bush | 333,599 | ... | ... | 28,664 | ... | ... | 362,263 |
| Working Capital Fund | ... | $11,633,412 | ... | ... | $(12,438,385) | 804,973 | ... |
| Restricted Grants | ... | 6,058,091 | ... | ... | (6,058,091) | ... | ... |
| Special Funds | | | | | | | |
| Astronomy | 3,009,032 | 162,230 | ... | 237,065 | (250,000) | ... | 3,158,327 |
| Ira S. and Mary Bowen | 923,200 | 50,372 | ... | 73,608 | (66,534) | ... | 980,646 |
| Bush Gift | 135,300 | 7,052 | ... | 10,305 | (15,364) | ... | 137,293 |
| Colburn | 788,599 | 44,017 | ... | 64,322 | (40,000) | ... | 856,938 |
| Scott E. Forbush | 42,907 | 2,523 | ... | 3,687 | ... | ... | 49,117 |
| Hale Relief | 30,160 | 1,773 | ... | 2,591 | ... | ... | 34,524 |
| Harkavy | 34,700 | 1,923 | ... | 2,810 | (2,000) | ... | 37,433 |
| Lundmark | 131,618 | 7,004 | ... | 10,235 | (12,507) | ... | 136,350 |
| Barbara McClintock | ... | 817 | 29,161 | 1,253 | ... | ... | 31,231 |
| Morganroth | 96,752 | 5,229 | ... | 7,642 | (7,817) | ... | 101,806 |
| Moseley Astronomy | 308,570 | 17,000 | ... | 24,842 | (19,450) | ... | 330,962 |
| Francis L. Moseley Gift | 208,058 | 9,294 | ... | 13,581 | (50,000) | ... | 180,933 |
| Roberts Memorial | 139,673 | 8,213 | ... | 12,001 | ... | ... | 159,887 |
| Special Instrumentation | 474,723 | 27,913 | ... | 40,790 | ... | ... | 543,426 |
| Special Opportunities | 287,633 | 16,913 | ... | 24,714 | ... | ... | 329,260 |
| Wood | 1,872,967 | 106,076 | ... | 155,006 | (68,955) | ... | 2,065,094 |
| Endowment and similar funds | 210,460,824 | 18,159,852 | 218,974 | 16,968,987 | (19,029,103) | ... | 226,779,534 |
| Plant Fund—in service | 14,755,333 | ... | ... | ... | ... | 166,345 | 14,921,678 |
| Totals | $225,216,157 | $18,159,852 | $218,974 | $16,968,987 | $(19,029,103) | $166,345 | $241,701,212 |

The accompanying notes are an integral part of these schedules.

Schedule 3

## Restricted Grants
### for the Year Ended June 30, 1989

| | Balance July 1, 1988 | New Grants | Expenses | Balance June 30, 1989 |
|---|---|---|---|---|
| *Federal Grants* | | | | |
| National Aeronautics and Space Administration | $ 814,303 | $ 126,632 | $ 249,756 | $ 691,179 |
| National Science Foundation | 1,254,708 | 1,080,727 | 1,198,731 | 1,136,704 |
| Public Health Service | 972,343 | 2,154,857 | 1,844,869 | 1,282,331 |
| U.S. Department of Agriculture | 37,233 | 15,000 | 40,251 | 11,982 |
| U.S. Department of Energy | 7,594 | 2,500 | 4,762 | 5,332 |
| U.S. Department of Interior | 15,655 | ... | (655) | 16,310 |
| U.S.—Israel BARD | 2,090 | 52,690 | 2,787 | 51,993 |
| Total federal grants | 3,103,926 | 3,432,406 | 3,340,501 | 3,195,831 |
| *Private Grants* | | | | |
| American Association for the Advancement of Science | ... | 4,000 | 2,228 | 1,772 |
| American Astronomical Society | ... | 2,000 | ... | 2,000 |
| American Cancer Society | 479,838 | 14,000 | 51,034 | 442,804 |
| American Society for Microbiology | ... | 12,000 | 4,373 | 7,627 |
| H. W. Babcock | 5,000 | ... | 5,000 | ... |
| California Institute of Technology | 41,112 | 61,222 | 74,664 | 27,670 |
| The Jane Coffin Childs Memorial Fund | ... | 21,000 | 20,845 | 155 |
| People's Republic of China | 4,285 | ... | ... | 4,285 |
| University of Delaware | 6,814 | ... | 5,648 | 1,166 |
| William R. Hewlett Lead Trust | 2,001,326 | 997,125 | 1,120,382 | 1,878,069 |
| The Howard Hughes Medical Institute | ... | 110,500 | 46,740 | 63,760 |
| Incorporated Research Institutions for Seismology | ... | 74,644 | 30,179 | 44,465 |
| The Johns Hopkins University | 53,378 | 182,043 | 184,018 | 51,403 |
| W. M. Keck Foundation | ... | 20,790 | 20,790 | ... |
| Leukemia Society of America | 26,680 | 76,140 | 25,617 | 77,203 |
| Life Sciences Research Foundation | 40,456 | (41,865) | (1,409) | ... |
| John D. and Catherine T. MacArthur Foundation | 4,634 | 76,250 | 80,822 | 62 |
| Marine Biological Laboratory | 4,078 | (4,078) | ... | ... |
| Lucille P. Markey Charitable Trust | 343,907 | 621,200 | 474,416 | 490,691 |
| The Andrew W. Mellon Foundation | 429,208 | 465,000 | 338,474 | 555,734 |
| Ambrose Monell Foundation | ... | 150,000 | 98,386 | 51,614 |
| Monsanto Company | 252 | 4,500 | 4,500 | 252 |
| National Academy of Sciences | 15,733 | ... | 15,733 | ... |
| Richard B. T. Roberts | 1,306 | ... | ... | 1,306 |
| John D. Rockefeller Foundation | 32,400 | ... | 5,536 | 26,864 |
| Vera C. Rubin | 4,347 | ... | ... | 4,347 |
| Damon Runyon-Walter Winchell Cancer Fund | 1,447 | ... | ... | 1,447 |
| Alfred P. Sloan Foundation | 14,624 | (8,946) | 5,678 | ... |
| The Teagle Foundation, Inc. | ... | 50,000 | 50,000 | ... |
| Weizmann Institute | 10,894 | 28,500 | 32,102 | 7,292 |
| Helen Hay Whitney Foundation | 47,583 | 41,333 | 21,834 | 67,082 |
| Total private grants | 3,569,302 | 2,957,358 | 2,717,590 | 3,809,070 |
| Total restricted grants | 6,673,228 | $6,389,764 | $6,058,091 | 7,004,901 |
| Less cash not yet received from grants | 3,826,544 | | | 4,181,721 |
| Deferred income | $2,846,684 | | | $2,823,180 |

The accompanying notes are an integral part of these schedules.

Schedule 4

## Schedule of Expenses
### for the Years Ended June 30, 1989 and 1988

| | 1989 | | | 1988* |
|---|---|---|---|---|
| | Endowment and Special | Restricted Grants | Total Expenses | Total Expenses |
| Salaries, fringe benefits, and payroll taxes | | | | |
| Salaries | $ 6,286,519 | $ 1,365,757 | $ 7,652,276 | $ 7,162,337 |
| Fringe benefits and payroll taxes | 1,761,142 | 364,613 | 2,125,755 | 1,971,571 |
| Total | 8,047,661 | 1,730,370 | 9,778,031 | 9,133,908 |
| Fellowship grants and awards | 595,918 | 436,390 | 1,032,308 | 993,770 |
| Equipment | | | | |
| Educational and research | 270,104 | 1,126,030 | 1,396,134 | 1,493,190 |
| Administrative and operating | 129,764 | 68,212 | 197,976 | 480,613 |
| Building (improvement) | ... | 246,056 | 246,056 | 648,522 |
| Total | 399,868 | 1,440,298 | 1,840,166 | 2,622,325 |
| General expenses | | | | |
| Educational and research supplies | 590,683 | 750,994 | 1,341,677 | 1,416,831 |
| Contract services | 176,698 | 66,201 | 242,899 | 238,655 |
| Building maintenance and repairs | 415,098 | 144,957 | 560,055 | 463,434 |
| Utilities | 564,588 | ... | 564,588 | 577,652 |
| Investment services | 686,344 | ... | 686,344 | 699,301 |
| Administrative | 309,527 | 7,324 | 316,851 | 253,221 |
| Computer services | 67,259 | 56,894 | 124,153 | 230,041 |
| Travel and meetings | 468,894 | 172,188 | 641,082 | 525,485 |
| Retiree health insurance | 273,954 | ... | 273,954 | 252,281 |
| General insurance | 266,012 | ... | 266,012 | 236,463 |
| Publications | 73,890 | 31,884 | 105,774 | 196,768 |
| Professional and consulting fees | 366,175 | 196,468 | 562,643 | 398,152 |
| Commissary | 46,807 | ... | 46,807 | 37,319 |
| Shop | 75,709 | ... | 75,709 | 61,089 |
| Telephone | 170,339 | ... | 170,339 | 127,210 |
| Postage and shipping | 153,843 | 8,332 | 162,175 | 148,722 |
| Books and subscriptions | 168,418 | ... | 168,418 | 150,847 |
| Miscellaneous | 38,034 | 31,084 | 69,118 | 50,190 |
| Total | 4,912,272 | 1,466,326 | 6,378,598 | 6,063,661 |
| Indirect costs | (984,707) | 984,707 | ... | ... |
| Total expenses | $12,971,012 | $ 6,058,091 | $19,029,103 | $18,813,664 |

*Restated for comparative purposes.

The accompanying notes are an integral part of these schedules.

# *Articles of Incorporation*

## Fifty-eighth Congress of the United States of America;

### At the Second Session,

**Begun and held at the City of Washington on Monday, the seventh day of December, one thousand nine hundred and three.**

---

## AN ACT

To incorporate the Carnegie Institution of Washington.

---

*Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,* That the persons following, being persons who are now trustees of the Carnegie Institution, namely, Alexander Agassiz, John S. Billings, John L. Cadwalader, Cleveland H. Dodge, William N. Frew, Lyman J. Gage, Daniel C. Gilman, John Hay, Henry L. Higginson, William Wirt Howe, Charles L. Hutchinson, Samuel P. Langley, William Lindsay, Seth Low, Wayne MacVeagh, Darius O. Mills, S. Weir Mitchell, William W. Morrow, Ethan A. Hitchcock, Elihu Root, John C. Spooner, Andrew D. White, Charles D. Walcott, Carroll D. Wright, their associates and successors, duly chosen, are hereby incorporated and declared to be a body corporate by the name of the Carnegie Institution of Washington and by that name shall be known and have perpetual succession, with the powers, limitations, and restrictions herein contained.

Sec. 2. That the objects of the corporation shall be to encourage, in the broadest and most liberal manner, investigation, research, and discovery, and the application of knowledge to the improvement of mankind; and in particular—

(a) To conduct, endow, and assist investigation in any department of science, literature, or art, and to this end to cooperate with governments, universities, colleges, technical schools, learned societies, and individuals.

(b) To appoint committees of experts to direct special lines of research.

(c) To publish and distribute documents.

(d) To conduct lectures, hold meetings, and acquire and maintain a library.

(e) To purchase such property, real or personal, and construct such building or buildings as may be necessary to carry on the work of the corporation.

(f) In general, to do and perform all things necessary to promote the objects of the institution, with full power, however, to the trustees hereinafter appointed and their successors from time to time to modify the conditions and regulations under which the work shall be carried on, so as to secure the application of the funds in the manner best adapted to the conditions of the time, provided that the objects of the corporation shall at all times be among the foregoing or kindred thereto.

SEC. 3. That the direction and management of the affairs of the corporation and the control and disposal of its property and funds shall be vested in a board of trustees, twenty-two in number, to be composed of the following individuals: Alexander Agassiz, John S. Billings, John L. Cadwalader, Cleveland H. Dodge, William N. Frew, Lyman J. Gage, Daniel C. Gilman, John Hay, Henry L. Higginson, William Wirt Howe, Charles L. Hutchinson, Samuel P. Langley, William Lindsay, Seth Low, Wayne MacVeagh, Darius O. Mills, S. Weir Mitchell, William W. Morrow, Ethan A. Hitchcock, Elihu Root, John C. Spooner, Andrew D. White, Charles D. Walcott, Carroll D. Wright, who shall constitute the first board of trustees. The board of trustees shall have power from time to time to increase its membership to not more than twenty-seven members. Vacancies occasioned by death, resignation, or otherwise shall be filled by the remaining trustees in such manner as the by-laws shall prescribe; and the persons so elected shall thereupon become trustees and also members of the said corporation. The principal place of business of the said corporation shall be the city of Washington, in the District of Columbia.

SEC. 4. That such board of trustees shall be entitled to take, hold and administer the securities, funds, and property so transferred by said Andrew Carnegie to the trustees of the Carnegie Institution and such other funds or property as may at any time be given, devised, or bequeathed to them, or to such corporation, for the purposes of the trust; and with full power from time to time to adopt a common seal, to appoint such officers, members of the board of trustees or otherwise, and such employees as may be deemed necessary in carrying on the business of the corporation, at such salaries or with such remuneration as they may deem proper; and with full power to adopt by-laws from time to time and such rules or regulations as may be necessary to secure the safe and convenient transaction of the business of the corporation; and with full power and discretion to deal with and expend the income of the corporation in such manner as in their judgment will best promote the objects herein set forth and in general to have and use all powers and authority necessary to promote such objects and carry out the purposes of the donor. The said trustees shall have further power from time

to time to hold as investments the securities hereinabove referred to so transferred by Andrew Carnegie, and any property which has been or may be transferred to them or such corporation by Andrew Carnegie or by any other person, persons, or corporation, and to invest any sums or amounts from time to time in such securities and in such form and manner as are permitted to trustees or to charitable or literary corporations for investment, according to the laws of the States of New York, Pennsylvania, or Massachusetts, or in such securities as are authorized for investment by the said deed of trust so executed by Andrew Carnegie, or by any deed of gift or last will and testament to be hereafter made or executed.

SEC. 5. That the said corporation may take and hold any additional donations, grants, devises, or bequests which may be made in further support of the purposes of the said corporation, and may include in the expenses thereof the personal expenses which the trustees may incur in attending meetings or otherwise in carrying out the business of the trust, but the services of the trustees as such shall be gratuitous.

SEC. 6. That as soon as may be possible after the passage of this Act a meeting of the trustees hereinbefore named shall be called by Daniel C. Gilman, John S. Billings, Charles D. Walcott, S. Weir Mitchell, John Hay, Elihu Root, and Carroll D. Wright, or any four of them, at the city of Washington, in the District of Columbia, by notice served in person or by mail addressed to each trustee at his place of residence; and the said trustees, or a majority thereof, being assembled, shall organize and proceed to adopt by-laws, to elect officers and appoint committees, and generally to organize the said corporation; and said trustees herein named, on behalf of the corporation hereby incorporated, shall thereupon receive, take over, and enter into possession, custody, and management of all property, real or personal, of the corporation heretofore known as the Carnegie Institution, incorporated, as hereinbefore set forth under "An Act to establish a Code of Law for the District of Columbia, January fourth, nineteen hundred and two," and to all its rights, contracts, claims, and property of any kind or nature; and the several officers of such corporation, or any other person having charge of any of the securities, funds, real or personal, books or property thereof, shall, on demand, deliver the same to the said trustees appointed by this Act or to the persons appointed by them to receive the same; and the trustees of the existing corporation and the trustees herein named shall and may take such other steps as shall be necessary to carry out the purposes of this Act.

SEC. 7. That the rights of the creditors of the said existing corporation known as the Carnegie Institution shall not in any manner be impaired by the

passage of this Act, or the transfer of the property hereinbefore mentioned, nor shall any liability or obligation for the payment of any sums due or to become due, or any claim or demand, in any manner or for any cause existing against the said existing corporation, be released or impaired; but such corporation hereby incorporated is declared to succeed to the obligations and liabilities and to be held liable to pay and discharge all of the debts, liabilities, and contracts of the said corporation so existing to the same effect as if such new corporation had itself incurred the obligation or liability to pay such debt or damages, and no such action or proceeding before any court or tribunal shall be deemed to have abated or been discontinued by reason of the passage of this Act.

**Sec. 8. That Congress may from time to time alter, repeal, or modify this Act of incorporation, but no contract or individual right made or acquired shall thereby be divested or impaired.**

Sec. 9. That this Act shall take effect immediately.

J G Cannon

*Speaker of the House of Representatives.*

Wm P Frye

*President of the Senate pro tempore.*

Roosevelt

# *By-Laws of the Institution*

*Adopted December 13, 1904. Amended December 13, 1910, December 13, 1912, December 10, 1937, December 15, 1939, December 13, 1940, December 18, 1942, December 12, 1947, December 10, 1954, October 24, 1957, May 8, 1959, May 13, 1960, May 10, 1963, May 15, 1964, March 6, 1967, May 3, 1968, May 14, 1971, August 31, 1972, May 9, 1974, April 30, 1976, May 1, 1981, May 7, 1982, May 3, 1985, May 9, 1986, May 15, 1987, May 6, 1988, and May 5, 1989.*

## ARTICLE I

### *The Trustees*

1.1. The Board of Trustees shall consist of up to thirty members as determined from time to time by the Board.

1.2. The Board of Trustees shall be divided into three classes approximately equal in number. The terms of the Trustees shall be such that those of the members of one class expire at the conclusion of each annual meeting of the Board. At each annual meeting of the Board vacancies resulting from the expiration of Trustees' terms shall be filled by their re-election or election of their successors. Trustees so re-elected or elected shall serve for terms of three years expiring at the conclusion of the annual meeting of the Board in the third year after their election. A vacancy resulting from the resignation, death, or incapacity of a Trustee before the expiration of his* term may be filled by election of a successor at or between annual meetings. A person elected to succeed a Trustee before the expiration of his term shall serve for the remainder of that term unless the Board determines that assignment to a class other than the predecessor's is appropriate. There shall be no limit on the number of terms for which a Trustee may serve, and a Trustee shall be eligible for immediate re-election upon expiration of his term.

1.3. No Trustee shall receive any compensation for his services as such.

1.4. Trustees shall be elected by vote of two-thirds of the Trustees present at a meeting of the Board of Trustees at which a quorum is present or without a meeting by written action of all of the Trustees pursuant to Section 4.6.

1.5. If, at any time during an emergency period, there be no surviving Trustee capable of acting, the President, the Director of each existing Department, or such of them as shall then be surviving and capable of acting, shall constitute a Board of Trustees *pro tem*, with full powers under the provisions of the Articles of Incorporation and these By-Laws. Should neither the President nor any such Director be capable of acting, the senior surviving Staff Member of each existing Department shall be a Trustee *pro tem* with full powers of a Trustee under the Articles of Incorporation and these By-Laws. It shall be incumbent on the Trustees *pro tem* to reconstitute the Board with permanent members within a reasonable time after the emergency has passed, at which time the Trustees *pro tem* shall cease to hold office. A list of Staff Member seniority, as designated annually by the President, shall be kept in the Institution's records.

1.6. A Trustee who resigns after having served at least six years and having reached age seventy shall be eligible for designation by the Board of Trustees as a Trustee Emeritus. A Trustee Emeritus shall be entitled to attend meetings of the Board but shall have no vote and shall not be counted for purposes of ascertaining the presence of a quorum. A Trustee Emeritus may be invited to serve in an advisory capacity on any committee of the Board except the Executive Committee.

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*A masculine pronoun as used in these By-Laws shall be deemed to include the corresponding female pronoun.

## ARTICLE II

### *Officers of the Board*

2.1. The officers of the Board shall be a Chairman of the Board, a Vice-Chairman, and a Secretary, who shall be elected by the Trustees, from the members of the Board, by ballot to serve for a term of three years. All vacancies shall be filled by the Board for the unexpired term; provided, however, that the Executive Committee shall have power to fill a vacancy in the office of Secretary to serve until the next meeting of the Board of Trustees.

2.2. The Chairman shall preside at all meetings and shall have the usual powers of a presiding officer.

2.3. The Vice-Chairman, in the absence or disability of the Chairman, shall perform the duties of the Chairman.

2.4. The Secretary shall issue notices of meetings of the Board, record its transactions, and conduct that part of the correspondence relating to the Board and to his duties.

## ARTICLE III

### *Executive Administration*

3.1. There shall be a President who shall be elected by ballot by, and hold office during the pleasure of, the Board, who shall be the chief executive officer of the Institution. The President, subject to the control of the Board and the Executive Committee, shall have general charge of all matters of administration and supervision of all arrangements for research and other work undertaken by the Institution or with its funds. He shall prepare and submit to the Board of Trustees and to the Executive Committee plans and suggestions for the work of the Institution, shall conduct its general correspondence and the correspondence with applicants for grants and with the special advisors of the Committee, and shall present his recommendations in each case to the Executive Committee for decision. All proposals and requests for grants shall be referred to the President for consideration and report. He shall have power to remove, appoint, and, within the scope of funds made available by the Trustees, provide for compensation of subordinate employees and to fix the compensation of such employees within the limits of a maximum rate of compensation to be established from time to time by the Executive Committee. He shall be *ex officio* a member of the Executive Committee.

3.2. The President shall be the legal custodian of the seal and of all property of the Institution whose custody is not otherwise provided for. He shall sign and execute on behalf of the corporation all contracts and instruments necessary in authorized administrative and research matters and affix the corporate seal thereto when necessary, and may delegate the performance of such acts and other administrative duties in his absence to other officers. He may execute all other contracts, deeds, and instruments on behalf of the corporation and affix the seal thereto when expressly authorized by the Board of Trustees or Executive Committee. He may, within the limits of his own authorization, delegate to other officers authority to act as custodian of and affix the corporate seal. He shall be responsible for the expenditure and disbursement of all funds of the Institution in accordance with the directions of the Board and of the Executive Committee, and shall keep accurate accounts of all receipts and disbursements. He shall, with the assistance of the Directors of the Departments, prepare for presentation to the Trustees and for publication an annual report on the activities of the Institution.

3.3. The President shall attend all meetings of the Board of Trustees.

3.4. The corporation shall have such other officers as may be appointed by the Executive Committee, having such duties and powers as may be specified by the Executive Committee or by the President under authority from the Executive Committee.

3.5. The President shall retire from office at the end of the fiscal year in which he becomes sixty-five years of age. The corporate officers appointed by the Executive Committee shall retire, and the Directors of Departments shall retire as Directors, at the end of the fiscal year in which they become sixty-five years of age, except as otherwise required by law or as retirement may be deferred by the Executive Committee.

## ARTICLE IV

### *Meetings and Voting*

4.1. The annual meeting of the Board of Trustees shall be held in the City of Washington, in the District of Columbia, in May of each year on a date fixed by the Executive Committee, or at such other time or such other place as may be designated by the Executive Committee, or if not so designated prior to May 1 of such year, by the Chairman of the Board of Trustees, or if he is absent or is unable or refuses to act, by any Trustee with the written consent of the majority of the Trustees then holding office.

4.2. Special meetings of the Board of Trustees may be called, and the time and place of meeting designated, by the Chairman, or by the Executive Committee, or by any Trustee with the written consent of the majority of the Trustees then holding office. Upon the written request of seven members of the Board, the Chairman shall call a special meeting.

4.3. Notices of meetings shall be given ten days prior to the date thereof. Notice may be given to any Trustee personally, or by mail or by telegram sent to the usual address of such Trustee. Notices of adjourned meetings need not be given except when the adjournment is for ten days or more.

4.4. The presence of a majority of the Trustees holding office shall constitute a quorum for the transaction of business at any meeting. An act of the majority of the Trustees present at a meeting at which a quorum is present shall be the act of the Board except as otherwise provided in these By-Laws. If, at a duly called meeting, less than a quorum is present, a majority of those present may adjourn the meeting from time to time until a quorum is present. Trustees present at a duly called or held meeting at which a quorum is present may continue to do business until adjournment notwithstanding the withdrawal of enough Trustees to leave less than a quorum.

4.5. The transactions of any meeting, however called and noticed, shall be as valid as though carried out at a meeting duly held after regular call and notice, if a quorum is present and if, either before or after the meeting, each of the Trustees not present in person signs a written waiver of notice, or consent to the holding of such meeting, or approval of the minutes thereof. All such waivers, consents, or approvals shall be filed with the corporate records or made a part of the minutes of the meeting.

4.6. Any action which, under law or these By-Laws, is authorized to be taken at a meeting of the Board of Trustees or any of the Standing Committees may be taken without a meeting if authorized in a document or documents in writing signed by all the Trustees, or all the members of the Committee, as the case may be, then holding office and filed with the Secretary.

4.7. During an emergency period the term "Trustees holding office" shall, for purposes of this Article, mean the surviving members of the Board who have not been rendered incapable of acting for any reason including difficulty of transportation to a place of meeting or of communication with other surviving members of the Board.

## ARTICLE V

### *Committees*

5.1. There shall be the following Standing Committees, *viz.* an Executive Committee, a Finance Committee, an Auditing Committee, a Nominating Committee, and an Employee Benefits Committee.

5.2. All vacancies in the Standing Committees shall be filled by the Board of Trustees at the next annual meeting of the Board and may be filled at a special meeting of the

Board. A vacancy in the Executive Committee and, upon request of the remaining members of any other Standing Committee, a vacancy in such other Committee may be filled by the Executive Committee by temporary appointment to serve until the next meeting of the Board.

5.3. The terms of all officers and of all members of Committees, as provided for herein, shall continue until their successors are elected or appointed. The term of any member of a Committee shall terminate upon termination of his service as a Trustee.

### *Executive Committee*

5.4. The Executive Committee shall consist of the Chairman, Vice-Chairman, and Secretary of the Board of Trustees, the President of the Institution *ex officio*, and, in addition, not less than five or more than eight Trustees to be elected by the Board by ballot for a term of three years, who shall be eligible for re-election. Any member elected to fill a vacancy shall serve for the remainder of his predecessor's term. The presence of four members of the Committee shall constitute a quorum for the transaction of business at any meeting.

5.5. The Executive Committee shall, when the Board is not in session and has not given specific directions, have general control of the administration of the affairs of the corporation and general supervision of all arrangements for administration, research, and other matters undertaken or promoted by the Institution. It shall also submit to the Board of Trustees a printed or typewritten report of each of its meetings, and at the annual meeting shall submit to the Board a report for publication.

5.6. The Executive Committee shall have power to authorize the purchase, sale, exchange, or transfer of real estate.

### *Finance Committee*

5.7. The Finance Committee shall consist of not less than five and not more than six members to be elected by the Board of Trustees by ballot for a term of three years, who shall be eligible for re-election. The presence of three members of the Committee shall constitute a quorum for the transaction of business at any meeting.

5.8. The Finance Committee shall have custody of the securities of the Institution and general charge of its investments and invested funds and shall care for and dispose of the same subject to the directions of the Board of Trustees. It shall have power to authorize the purchase, sale, exchange, or transfer of securities and to delegate this power. For any retirement or other benefit plan for the staff members and employees of the Institution, it shall be responsible for supervision of matters relating to investments, appointment or removal of any investment manager or advisor, reviewing the financial status and arrangements, and appointment or removal of any plan trustee or insurance carrier. It shall consider and recommend to the Board from time to time such measures as in its opinion will promote the financial interests of the Institution and improve the management of investments under any retirement or other benefit plan. The Committee shall make a report at the annual meeting of the Board.

### *Auditing Committee*

5.9. The Auditing Committee shall consist of three members to be elected by the Board of Trustees by ballot for a term of three years.

5.10. Before each annual meeting of the Board of Trustees, the Auditing Committee shall cause the accounts of the Institution for the preceding fiscal year to be audited by public accountants. The accountants shall report to the Committee, and the Committee

shall present said report at the ensuing annual meeting of the Board with such recommendations as the Committee may deem appropriate.

*Nominating Committee*

5.11. The Nominating Committee shall consist of the Chairman of the Board of Trustees *ex officio* and, in addition, three Trustees to be elected by the Board by ballot for a term of three years, who shall be eligible for re-election, but, after serving for two consecutive terms, not until after the lapse of one year. Any member elected to fill a vacancy shall serve for the remainder of his predecessor's term. The Chairman of the Board shall appoint a member of the Committee as Chairman for a term expiring no later than the expiration of his term as a member.

5.12. Sixty days prior to an annual meeting of the Board the Nominating Committee shall notify the Trustees by mail of the vacancies to be filled in membership of the Board. Each Trustee may submit nominations for such vacancies. Nominations so submitted shall be considered by the Nominating Committee, and ten days prior to the annual meeting the Nominating Committee shall submit to members of the Board by mail a list of the persons so nominated, with its recommendations for filling existing vacancies on the Board and its Standing Committees. No other nominations shall be received by the Board at the annual meeting except with the unanimous consent of the Trustees present.

*Employee Benefits Committee*

5.13. The Employee Benefits Committee shall consist of not less than three and not more than four members to be elected by the Board of Trustees by ballot for a term of three years, who shall be eligible for re-election, and the Chairman of the Finance Committee *ex officio*. Any member elected to fill a vacancy shall serve for the remainder of his predecessor's term.

5.14. The Employee Benefits Committee shall, subject to the directions of the Board of Trustees, be responsible for supervision of the activities of the administrator or administrators of any retirement or other benefit plan for staff members and employees of the Institution, except that any matter relating to investments or to the appointment or removal of any trustee or insurance carrier under any such plan shall be the responsibility of the Finance Committee. It shall receive reports from the administrator or administrators of the employee benefit plans with respect to administration, benefit structure, operation, and funding. It shall consider and recommend to the Board from time to time such measures as in its opinion will improve such plans and the administration thereof. The Committee shall submit a report to the Board at the annual meeting of the Board.

## ARTICLE VI

*Financial Administration*

6.1. No expenditure shall be authorized or made except in pursuance of a previous appropriation by the Board of Trustees, or as provided in Section 5.8 of these By-Laws.

6.2. The fiscal year of the Institution shall commence on the first day of July in each year.

6.3. The Executive Committee shall submit to the annual meeting of the Board a full statement of the finances and work of the Institution for the preceding fiscal year and a detailed estimate of the expenditures of the succeeding fiscal year.

6.4. The Board of Trustees, at the annual meeting in each year, shall make general appropriations for the ensuing fiscal year; but nothing contained herein shall prevent the Board of Trustees from making special appropriations at any meeting.

6.5. The Executive Committee shall have general charge and control of all appropriations made by the Board. Following the annual meeting, the Executive Committee may allocate these appropriations for the succeeding fiscal year. The Committee shall have full authority to reallocate available funds, as needed, and to transfer balances.

6.6. The securities of the Institution and evidences of property, and funds invested and to be invested, shall be deposited in such safe depository or in the custody of such trust company and under such safeguards as the Finance Committee shall designate, subject to directions of the Board of Trustees. Income of the Institution available for expenditure shall be deposited in such banks or depositories as may from time to time be designated by the Executive Committee.

6.7. Any trust company entrusted with the custody of securities by the Finance Committee may, by resolution of the Board of Trustees, be made Fiscal Agent of the Institution, upon an agreed compensation, for the transaction of the business coming within the authority of the Finance Committee.

6.8. The property of the Institution is irrevocably dedicated to charitable purposes, and in the event of dissolution its property shall be used for and distributed to those charitable purposes as are specified by the Congress of the United States in the Articles of Incorporation, Public Law No. 260, approved April 28, 1904, as the same may be amended from time to time.

## ARTICLE VII

### *Amendment of By-Laws*

7.1. These By-Laws may be amended at any annual or special meeting of the Board of Trustees by a two-thirds vote of the members present, provided written notice of the proposed amendment shall have been served personally upon, or mailed to the usual address of, each member of the Board twenty days prior to the meeting.

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